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INTERPRETATION OF THE MIOCENE CARL CREEK LIMESTONE, NORTHWESTERN QUEENSLAND.

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ABSTRACT

The Miocene Carl Creek Limestone of Riversleigh, northwestern Queensland, is a clastic deposit composed of sediments characteristic of humid alluvial fans and tufas (*sensu* Pedley 1990). Factors influencing clastic-carbonate yield and processes of carbonate deposition indicate that the calciclastic alluvial outwash comprising the Carl Creek Limestone could only have accumulated under relatively dry, perhaps semi-arid, conditions. This palaeoclimatic interpretation for northern Australia during the Miocene is consistent with interpretations from other data-sets. Other limestone formations of similar age, widely distributed across northern Australia in various sedimentary basins represent different depositional environments, but are here related to the Carl Creek Limestone through a hypothetical hydraulic flow system. Archer *et al.* (1989) postulated the former presence of rainforest at Riversleigh on the basis of an exceptionally diverse mammal fauna, interpreted by them as being a sympatric assemblage. Under climatic conditions postulated here for the region during the Miocene, any rainforest was probably restricted to the proximity of perennial, spring-fed streams within the Carl Creek Limestone depositional basin. The high mammal species diversity in the Carl Creek Limestone might result from a combination of a rainforest-adapted proximal community, and mesically-adapted distant communities whose members travelled to permanent water sources during dry periods. Thus, radiation of Australia's marsupial faunas into drier habitats was already well advanced by earliest Carl Creek Limestone times, and Miocene rainforest at Riversleigh represented a refugium for rainforest-adapted taxa.

Keywords: Carl Creek Limestone, Miocene, Queensland, calciclastic alluvium, tufa, karst, palaeoclimate, palaeoenvironment.

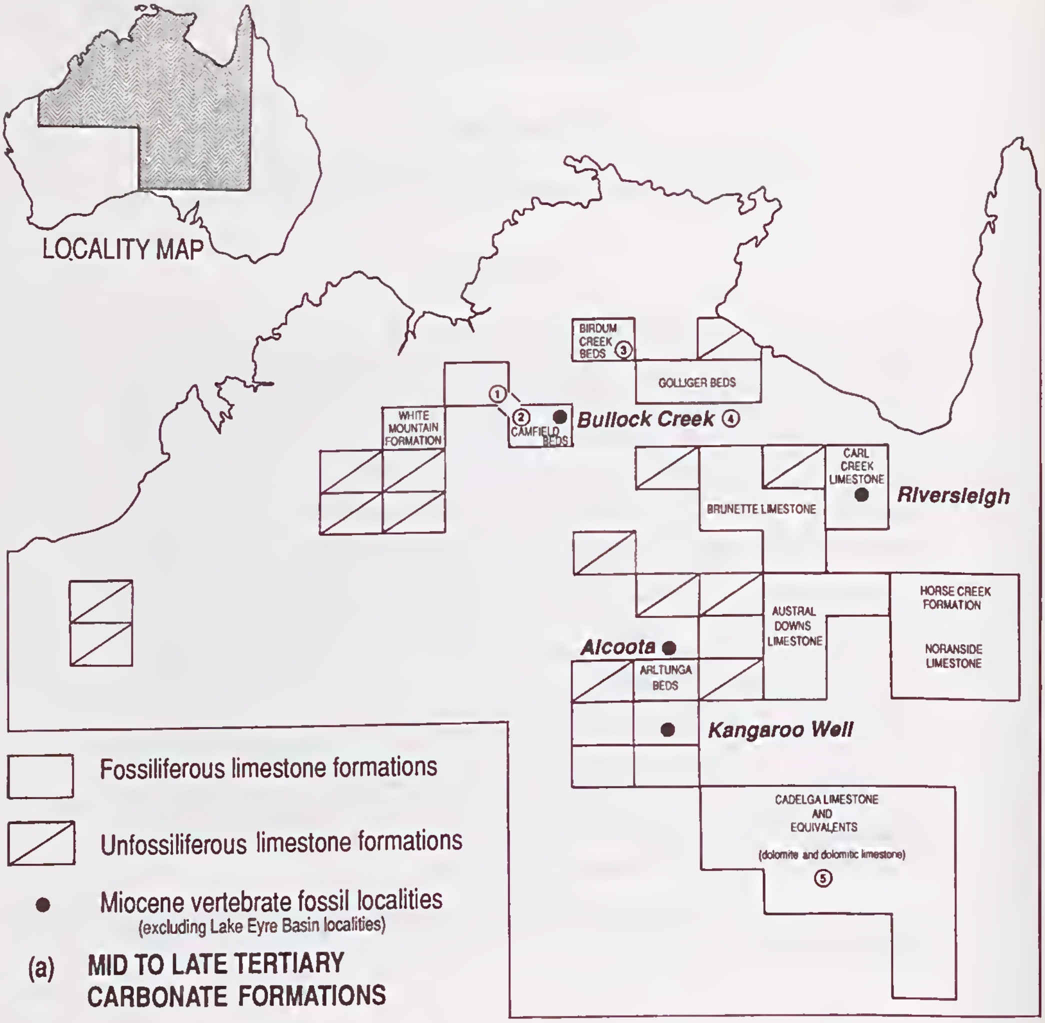
INTRODUCTION

This paper constitutes an initial report on a detailed study in progress of the geology of the Carl Creek Limestone at Riversleigh, northwestern Queensland. As outlined below, the Carl Creek Limestone is one of many limestone formations distributed across the northern half of Australia, west of the Great Dividing Range (Fig. 1). These formations appear to have been deposited during the Miocene, and their geographic and temporal distribution reflects common factors in their genesis.

A general model for continental carbonate deposition in Australia is proposed, based on preliminary interpretations of the Carl Creek Limestone, observations made of other formations, and previous studies reported in the literature. Sedimentological data are used to reconstruct palaeoenvironmental conditions prevailing across northern Australia during the Miocene in general, and at Riversleigh in particular, and provide a means of testing environmental reconstructions based on vertebrate palaeontology.

AGE AND DISTRIBUTION OF LIMESTONE FORMATIONS IN NORTHERN AUSTRALIA

An understanding of the Cainozoic stratigraphy of Australia in the region west of the Great Dividing Range has evolved slowly. Cainozoic sediments are typically thin, unlithified, poorly



(a) MID TO LATE TERTIARY CARBONATE FORMATIONS

(b) CAINOZOIC SEDIMENTARY BASINS

(c) PALYGORSKITE DISTRIBUTION ⑨

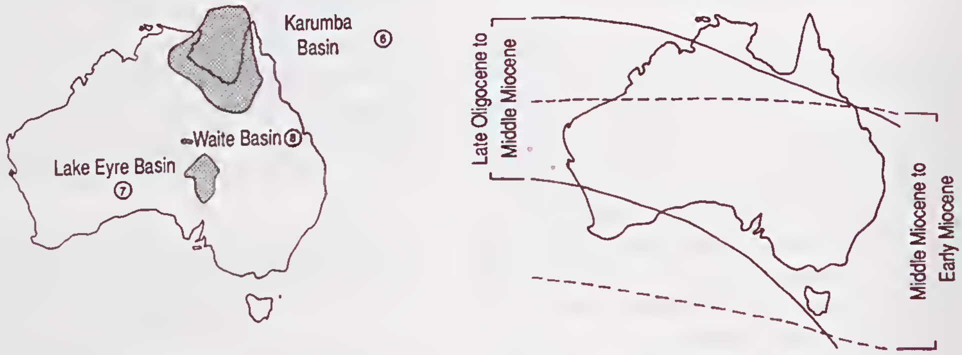


Fig. 1. a, plot of 1:250 000 map sheet areas containing Miocene carbonates; **b**, Cainozoic sedimentary basins referred to in the text, and (**c**) distribution of palygorskite clays in the mid to late Tertiary. Compiled from Lloyd 1965a and (1) Sweet (1973), (2) Bultitude (1973), (3) Randal (1969), (4) Plane and Gatehouse (1968), (5) Wopfner (1974), (6) Senior *et al.* (1980), (7) Wells and Callen (1986), (8) Woodburne (1967) and (9) Callen (1984).

exposed in outcrop and often deeply weathered. Apart from duricrusts (indurated weathered surfaces), only the carbonates are lithified and as a consequence of their relative durability, stand out in relief in the landscape and are amenable to study in outcrop. Historically, the major handicap to the development of a stratigraphic framework has been the lack of effective means of correlation. Over the past 50 years, lithostratigraphic techniques and biostratigraphy have advanced to the stage where tentative regional correlation charts have been proposed, such as that of Smart *et al.* (1980:Table 7) which extends from the Gulf of Carpentaria, west into the Northern Territory, and south into the desert regions of South Australia.

The Cainozoic geological history of the region is characterised by long periods of subaerial weathering interspersed with shorter term depositional events (e.g. Wopfner 1974). The weathered surfaces are morphological features of great lithostratigraphic value, equal to that of deposited units themselves (Wopfner 1974, Grimes 1979, Smart *et al.* 1980). Smart *et al.* (1980:70) describe the relationship of weathered surfaces to deposited formations through a cycle of events. Each cycle commences with uplift or some other event that initiates the active phase of the cycle. Erosion occurs in the higher, uplifted areas, and sediment is transported to, and deposited in, the lower downwarped areas. A diachronous unconformity surface forms as the depositional area expands or shifts. The process continues until the uplands are worn down and the potential energy of the system is reduced. The passive phase of the cycle is characterised by a long period of deep weathering of a more or less planar land - surface, and results in a terminal weathered surface. A new cycle begins with renewed tectonism or other event. In Australian continental stratigraphy, terminal weathered surfaces represent mappable units that serve as marker horizons over large areas (e.g. Hays 1967). Some have been successfully dated using palaeomagnetic methods (e.g. Idnurm and Senior 1978).

Relative ages of geographically-isolated formations containing vertebrate fossils have been established from the stage-of-evolution of marsupials (Woodburne *et al.* 1985). Primary support for the scheme of Woodburne *et al.* (1985), as it covers the Miocene, is derived from the geology and palaeontology of the Lake Eyre Basin of South Australia. In the Lake Eyre Basin, vertebrate faunas (Local Faunas) are in superposed formations, providing chronostratigraphic support to the interpretations of marsupial stage-of-evolution. From within the Etadunna Formation, geochronological constraints are provided by palaeobotanical and foraminiferal correlation to sequences outside the region, and to a single radiometric date on illite (Norrish and Pickering 1983), while magnetostratigraphic studies suggest an early Pliocene age for the Tirari Formation (Tedford *et al.* 1992). The age interpretations for the Etadunna Formation are not all consistent, ranging from late Oligocene to mid Miocene. An early Miocene age is shown for the Etadunna Formation in Figure 2 (*contra* Woodburne *et al.* 1985), but the relative ages of other formations containing Local Faunas are not in dispute.

Because of difficulties in lithostratigraphic correlation within the formation, each concentration of vertebrate fossils sampled from the Carl Creek Limestone is initially designated a unique Local Fauna (Archer *et al.* 1989). For the purposes of discussion, Archer *et al.* (1989) group Local Faunas of apparently similar age, geographic position and lithofacies into discrete "systems". In this paper, these "systems" are redefined to have only biostratigraphic meaning (Fig. 2), in order to clearly separate interpretations of age from any other attributes.

Lloyd (1965a) compiled the then available data on the distribution of Tertiary sediments in northern Australia, and reported on the occurrence of the foraminiferan *Ammonia beccarii* in the White Mountain Formation, Brunette Limestone and Austral Downs Limestone (Lloyd 1965b). *Ammonia beccarii* is not a good index fossil, ranging from the Lower Miocene to Recent, but does provide a maximum age for these formations. However, the three formations also contain terrestrial and freshwater gastropods found in the Carl Creek Limestone (Riversleigh Local Fauna of Tedford 1967; part of "system A" of Archer *et al.* 1989), and the un-named formation containing the Kangaroo Well Local Fauna (McMichael 1965). There are insufficient data to establish a biostratigraphic utility for the gastropods, but Lloyd (1965a:126) considered their distribution, other faunal consistencies such as the presence of ostracodes, together with the geomorphological interpretations of geologists mapping the region, as sufficient basis for assigning fossiliferous limestones to the Miocene. The subsequent recognition of the Camfield Beds and the discovery of the Bullock Creek Local Fauna (Randal and Brown 1967, Plane and

Gatehouse 1968, Bultitude 1973) and Birdum Creek Beds (Randal 1969) are consistent with this interpretation, but do not provide further constraints on age. Gastropods in the Camfield and Birdum Creek Beds, and Riversleigh "systems B and C" have not been described.

Lloyd (1965b) attributed the distribution of *A. beccarii* to a marine influence, postulating a widespread northern Australian marine transgression possibly co-inciding with early Miocene transgressions in southern Australia. Implicitly at least, Lloyd (1965) favours an earlier Miocene age for the White Mountain Formation, Brunette Limestone and Austral Downs Limestone.

Figure 2 portrays the probable maximum time-span of limestone deposition across northern Australia. It represents a relatively brief episode of mid to late-Tertiary sedimentation, probably ceasing before Waite Formation (Alcoota Local Fauna) time. The Carl Creek Limestone is of particular interest because it provides some good exposures in outcrop, contains a strikingly rich assemblage of vertebrate fossils, and is diachronous, apparently spanning the complete time-range of limestone deposition.

GEOLOGY OF THE CARL CREEK LIMESTONE

Previous investigations. The Carl Creek Limestone was named by Jack (1896), who quotes a more detailed report (Jack 1885) of his

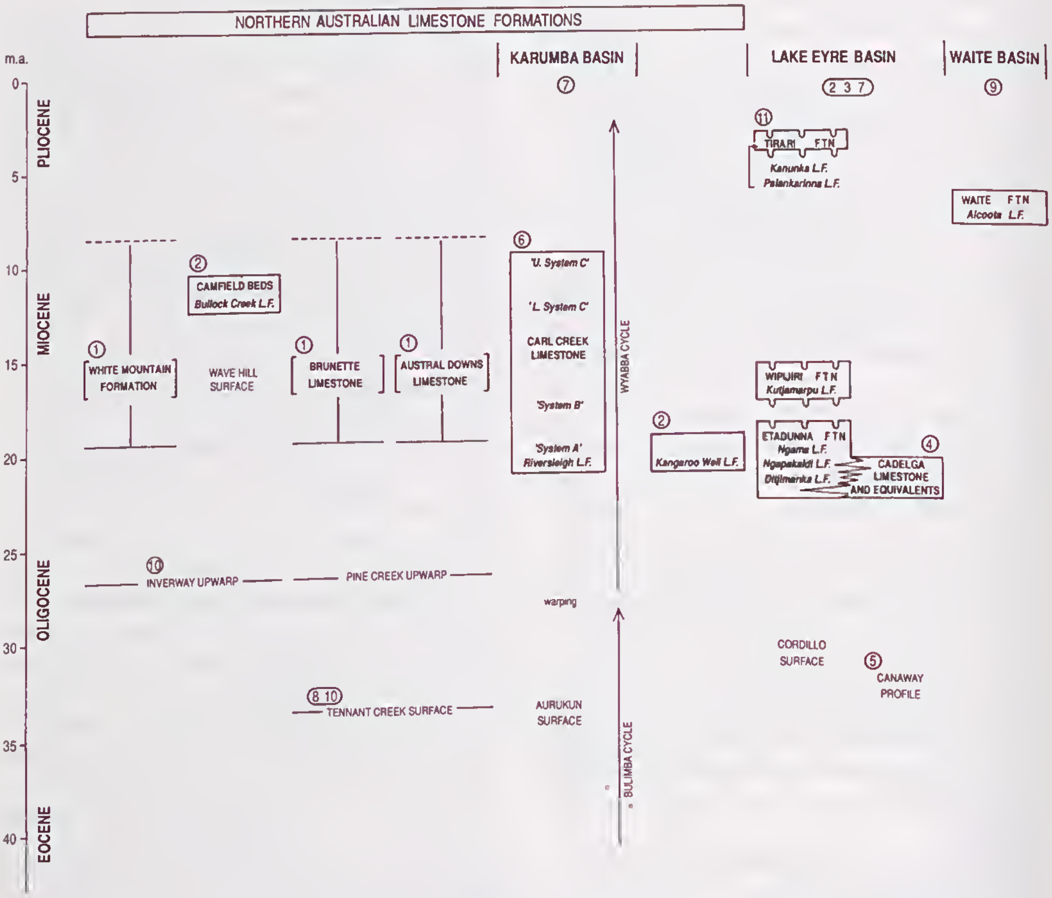


Fig. 2. Correlation chart of northern Australian limestone formations, and other selected formations and weathered surfaces providing geochronological control. Compiled from (1) Lloyd (1965a, 1965b), (2) Woodburne *et al.* (1985), (3) Wells and Callen (1986), (4) Wopfner (1974), (5) Idnurm and Senior (1978), (6) Archer *et al.* (1989), (7) Senior *et al.* (1980), (8) Grimes (1980), (9) Woodburne (1967), (10) Hays (1967) and Tedford (11) *et al.* (1991). The ages of the Wave Hill Surface and Inverway Upwarp are uncertain. The geochronology shown for them is an interpretation of details presented in Hays (1967), specifically (i) the Inverway Upwarp pre-dates the Wave Hill Surface, (ii) the Wave Hill Surface post-dates the Tennant Creek Surface, (iii) the Inverway Upwarp may be genetically related to the Pine Creek Upwarp, and (iv) the White Mountain Formation was deposited during the formation of the Wave Hill Surface.

discovery in 1881, behind the Police Barracks at Carl Creek, of a "hard yellowish limestone, horizontally bedded, unconformably overlying the nearly vertical sandstones etc, which rises on the right bank of the O'Shanassy to a greater elevation than the limestone" (Jack 1896:73). This description of the unit and the location of the outcrop is accurate, though minimal.

Jack (1896) believed, on geomorphological grounds, that the Carl Creek Limestone was the same as that mentioned by Daintree (1872), who referred to a shell of *Tellina* (a marine pelecypod) "from a bed of horizontal limestone at the head of the Gregory on the Barkly Tableland and forwarded to me by Rev. W.B. Clark of Sydney". Jack (1885,1896) makes no mention of fossils in the Carl Creek Limestone, but on the basis of his correlation with Daintree's (1872) stratum, thought the deposit to be Cretaceous, or possibly Lower Silurian, according to the two hypotheses then current on the age of Barkly Tableland strata. Jack (1896) was aware that limestones of varying ages might be present, a conclusion also reached by Danes (1911) who studied karst development in the region (Danes 1911, 1916).

The earliest report of fossils in the Carl Creek Limestone comes from Cameron (1901). Two species of gastropod, one freshwater and one terrestrial, identified by R. Etheridge Jr in Cameron (1901:14) as *Helix* and *Isodora* (*Therrites forsteriana* and *Isodora* near *I. pectorosa*), were found at the Carl Creek outcrop. Fragments of marsupial bones were found "in the same limestone at a point near the Verdon Rock, a few miles south of Verdon Creek" (Cameron 1901:14). The marsupials were assigned to the family Nototheriidae by de Vis (in Cameron 1901:14). On the basis of the palaeontology, lithology and structure, Cameron (1901) clarified the distinction of the Carl Creek Limestone, which he considered to be Post-Tertiary, from the much older limestones of the Barkly Tableland. Cameron (1901) also provides the earliest interpretation of the geology of the Carl Creek Limestone. Unfortunately, the accompanying map to Cameron's (1901) report greatly exaggerated the extent of the Carl Creek Limestone. Ball (1911), reporting on mining activities and the geology of the Burketown Mineral Field, centred to the north of the study area, realised that a mistake had been made in mapping, but assigned even more of what is now recognised as Cambrian outcrop to the Post-Tertiary (i.e. Carl Creek Limestone). In addition to an account of prevailing stratigraphic confusion, Ball (1911) provides some interesting details of geomorphic evolution of the area, including evidence for relatively recent tectonism.

Subsequent authors refer to the Carl Creek Limestone by a variety of synonyms. David (1914:255), in referring to the formation as a "*Helicidae* limestone" was not proposing a formal name, but was using *Helicidae* as an adjective to deseribe a lithology: he also refers to a *Helicidae* sandstone from the Bass Strait islands, *Cellepora gambierensis* limestone from the Australian Bight, and so on. Nevertheless, "Helicidae Limestone" gained acceptance (e.g. Bryan 1928, Whitehouse 1940, Bryan and Jones 1944). Chapman (1937, cited in Bryan and Jones 1944:38) refers to it as "*Helix* Sandstone", while Noakes and Traves (1954:40) proposed the name "Verdon Limestone" for:

> "... isolated outcrops (occurring) as poorly-bedded deposits which form the cap of mesas in the vicinity of Riversleigh Station, in the Gulf Fall. The limestone is tough, crystalline to amorphorus, and massive, and is about 40ft thick. It contains abundant pebbles of chert some of which has been derived from Cambrian Limestone, and a bed in which shells and fossil bones have been found. Palaeontological evidence is not yet conclusive and the limestone could be either Cretaceous or Tertiary in age."

Noakes and Traves (1954) do not provide references for the literature to which they allude, but there can be no doubt that they refer to the Carl Creek Limestone. The name Carl Creek Limestone was resurrected by Paten (1960) and followed by later workers. The earliest reasonably detailed study of the geology of the Carl Creek Limestone was included by Whitehouse (1940) in an account of Cainozoic limestone formations across Queensland and the eastern Northern Territory. Whitehouse (1940) provides few lithological descriptions of the Carl Creek Limestone, but gives a useful account of stratigraphy, depositional setting, and some comparisons with recent carbonate sedimentation in the Gregory River. He assigned the formation to the Pliocene and, like Cameron (1901), postulated a relatively dry climate during Carl Creek Limestone time. Whitehouse (1940) also found evidence that the limestones he examined in western Queensland occurred stratigraphically between two regionally-extensive weathered surfaces.

During a brief visit to Riversleigh in 1963, Richard Tedford and co-workers collected enough marsupial fossils to firmly establish a mid-Tertiary age for the Carl Creek Limestone (late Oligocene: Tedford 1967; Archer *et al.* 1989: mid-Miocene; Woodburne *et al.* 1985). Tedford (1967) provides good lithological descriptions, a number of stratigraphic sections and an interpretation of the depositional environment.

The geology of northwestern Queensland was investigated by geologists of the Bureau of Mineral Resources, Geology and Geophysics (BMR) and Geological Survey of Queensland (GSQ) as part of a major study started in 1969. A review of the Tertiary geology, and references to earlier literature is provided by Smart *et al.* (1980). As part of the project, BMR and GSQ issued a 1:100,000 scale geological map of the Lawn Hill Region (Sweet and Hutton 1982), which includes the area of the Carl Creek Limestone. Grimes (1974) names and describes the Gregory Limestone, cropping out on the Carpentaria Plain north of the study area, as a possible facies equivalent of the Carl Creek Limestone.

Further palaeontological investigations by Michael Archer and associates during the 1980s led to the recognition of additional outcrop in the western part of the study area, and discovery of new and very diverse faunas of apparently younger age than the Riversleigh Local Fauna described by Tedford (1967) (Archer *et al.* 1986). The study of these faunas is still in progress. The most recent summary of palaeontological activities in progress at Riversleigh and preliminary interpretations are presented in Archer *et al.* (1989).

Depositional setting. The Carl Creek Limestone crops out as a series of small mesas and poorly-exposed rubbly outcrops along a 35 kilometre stretch of the Gregory River drainage system on Riversleigh Station (Fig. 3a). Erosion has reduced the area of outcrop to about 25 km^2. In the southwest, basement to the Carl Creek Limestone consists of essentially flat-lying Cambrian sediments. These are composed of limestone and dolomite with bands of chert nodules, (Thorntonia Limestone) and minor phosphorite, chert and chert breccia (Border Waterhole Formation) of the Late Proterozoic to Devonian Georgina Basin (Fig. 3b). Within the study area, the Cambrian carbonates have been largely stripped away, leaving a coarse lag of chert nodules and other siliceous remnants over the landscape. Technically, this lag-deposit represents a post-Cambrian weathered surface, but is mapped as Cambrian in Sweet and Hutton (1982), which is a satisfactory arrangement (Fig. 3b) for discussions presented in this paper. The Cambrian carbonate residuals show advanced karst development. Flat-lying Late Jurassic or Early Cretaceous fluvial sandstones and conglomerates rest unconformably on the Proterozoic basement along the northern part of the study area. No Carl Creek Limestone is deposited directly upon the Mesozoic sediments.

To the northwest, the Carl Creek Limestone is deposited on folded and faulted sandstones, siltstones and conglomerates of the Proterozoic Lawn Hill Platform. The Proterozoic crops out as strike ridges trending northwest-southeast. The linear contact between the Georgina Basin and Lawn Hill Platform parallels the Termite Range Fault, a major structural feature in the Lawn Hill Platform, suggesting that the contact is a remaining manifestion of a fault scarp of Cambrian limestone. Faults have been recorded in the study area in the Cambrian sediments, and have apparently resulted from further movement along pre-existing faults in the Proterozoic basement.

The Gregory River, and its tributary, the O'Shanassy River, are perennial streams maintained by spring-flow discharging from a major aquifer centred to the southwest beneath the Barkly Tableland. Carl Creek, from which the Tertiary limestone takes its name, is a minor distributary of the Gregory River, flowing into the O'Shanassy upstream of the confluence of the two larger rivers. Formerly, it may have been the major channel of the Gregory River. River water is rich in dissolved calcium carbonate, and localised barrage tufa formation presently occurs at rapids on the river.

In the study area, the landscape has a relief of about 160m, with the Proterozoic strike-ridges peaking at about 260m A.H.D. (Australian Height Datum: approximately sea-level). Outside the study area to the southwest, the Cambrian carbonates reach an elevation of 200m to 300m A.H.D. on the Barkly Tableland. The Carl Creek Limestone is restricted to between the 120m and 200m A.H.D. topographic contours.

The Gregory and O'Shanassy Rivers are superposed drainages, cutting across structure in the Proterozoic basement. The confinement of the Carl Creek Limestone to the present Gregory drainage system, and topographic relationships, indicate that the Gregory River valley is an ancient feature, formed in pre-Carl Creek Limestone times.

Stratigraphy. The thickest exposures (about 30m maximum) of Carl Creek Limestone are

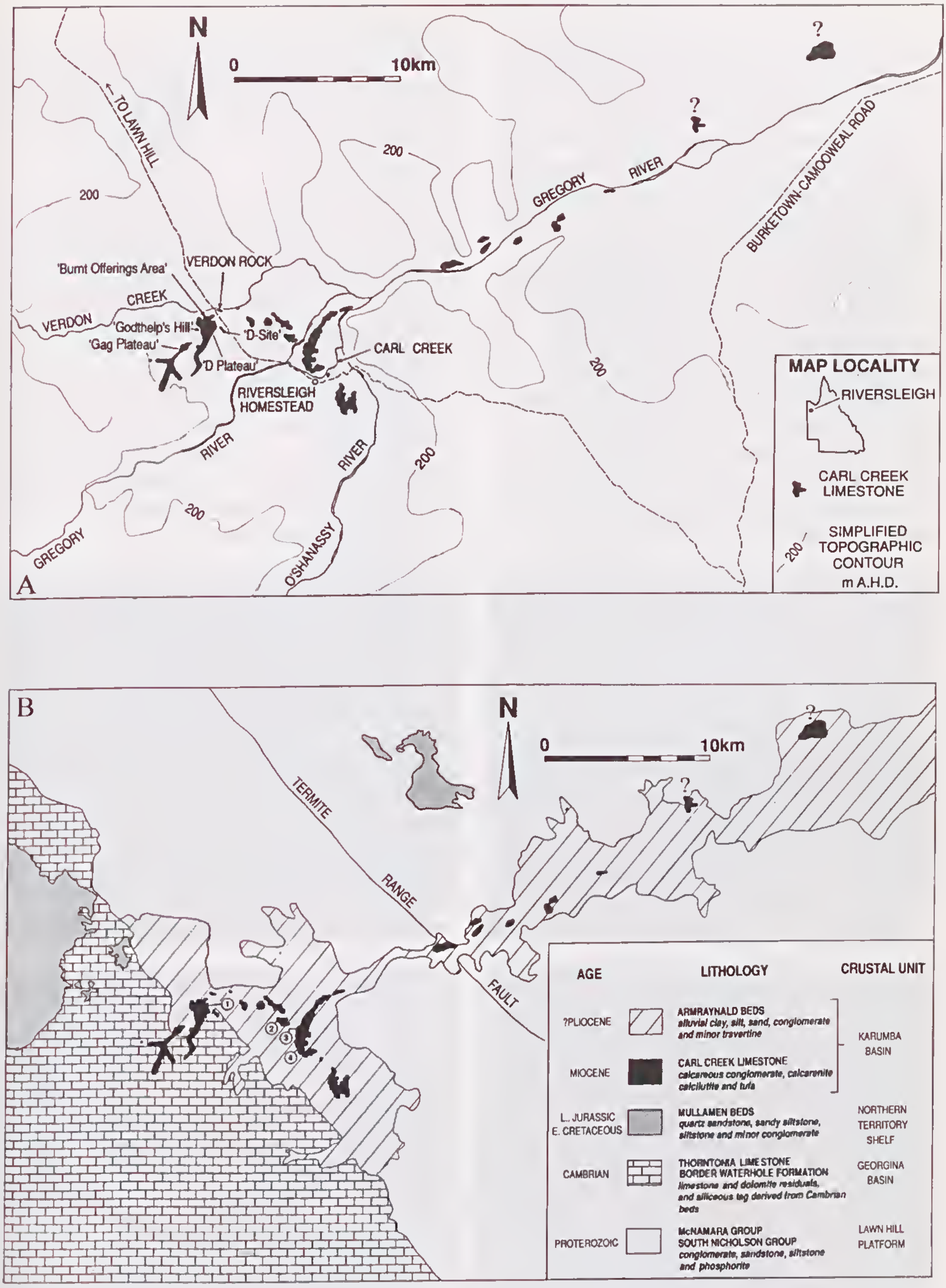


Fig. 3. a, Distribution of the Carl Creek Limestone in relation to geographical features; **b**, geology of the study area. Informal geographical place-names used by palaeontologists are shown in inverted commas. The position of the Verdon Rock is taken from Ball (1911): the current topographic map of the area identifies a Cambrian limestone mesa five kilometres to the northwest as the Verdon Rock.

found on mesas (Fig. 4a) in the southwestern part of the study area: to the northeast, ?Pliocene and younger alluvium partially buries the formation, which may be expressed at the surface by little more than a mound of limestone rubble. On the mesas, the limestone has been etched into a karst topography. Clints, grikes, rillenkarren, kamenitza and lapies are common surface features at the edges of the escarpments (Fig. 4b,c), while large blocks have slumped onto the scree slopes.

Irregular and discontinuous bedding planes, delimiting sedimentary units up to three metres thick are discernible on the escarpments. The beds are horizontal or dip at low angles. At the tops of the mesas, a thin mantle of soil and regolith (Fig. 4d) often obscures these contacts, while scree around the base masks the lowest units and their contact with basement. On the ground, bedding is difficult to trace laterally. The generally massive appearance of these large-scale beds, and the formation in general, results from the effect of the surface-weathering of a limestone of fairly uniform bulk composition, and the appearance in outcrop belies the textural heterogeneity and finer-scale bedding geometries described below. Often the best clues to primary depositional texture are the siliceous clasts that stand out in relief.

The vertical and areal distribution of lithologies and relationship of the Tertiary limestone to the undulating basement are summarised in a series of stratigraphic logs in Figure 5, with additional stratigraphic information shown in Figures 6 and 7. Assuming an average thickness of 20m for the formation, over an outcrop area of 25km^2, the Carl Creek Limestone has an estimated volume of 0.5km^3. The extent of the original depositional basin is more difficult to determine, but Fig. 3a indicates deposition was confined to a relatively narrow valley, probably no wider than the area encompassed by the present 200m topographic contour.

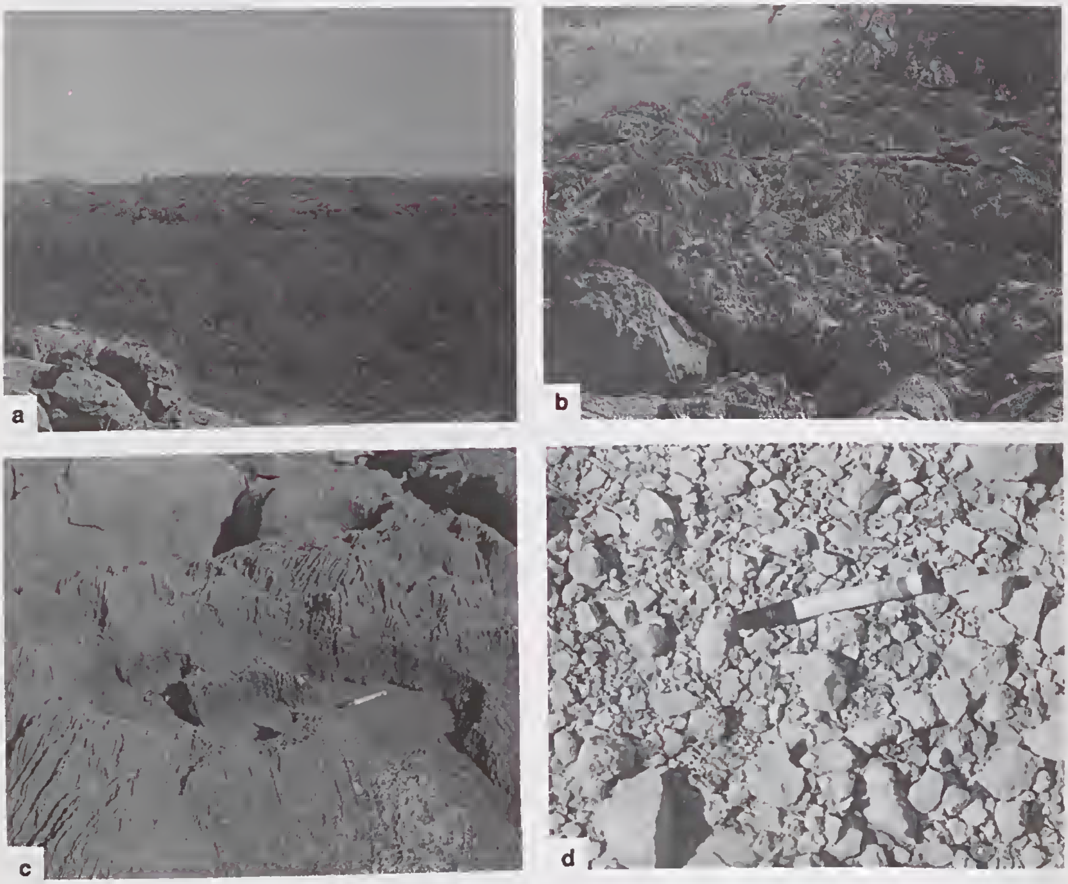


Fig. 4. a, A mesa of Carl Creek Limestone: the thickly-vegetated zone in the foreground bounds the Gregory River; **b** and **c**, etched limestone on the mesa escarpment; **d**, recent colluvium developed on the Carl Creek Limestone. The pen used for scale is 15cm long.

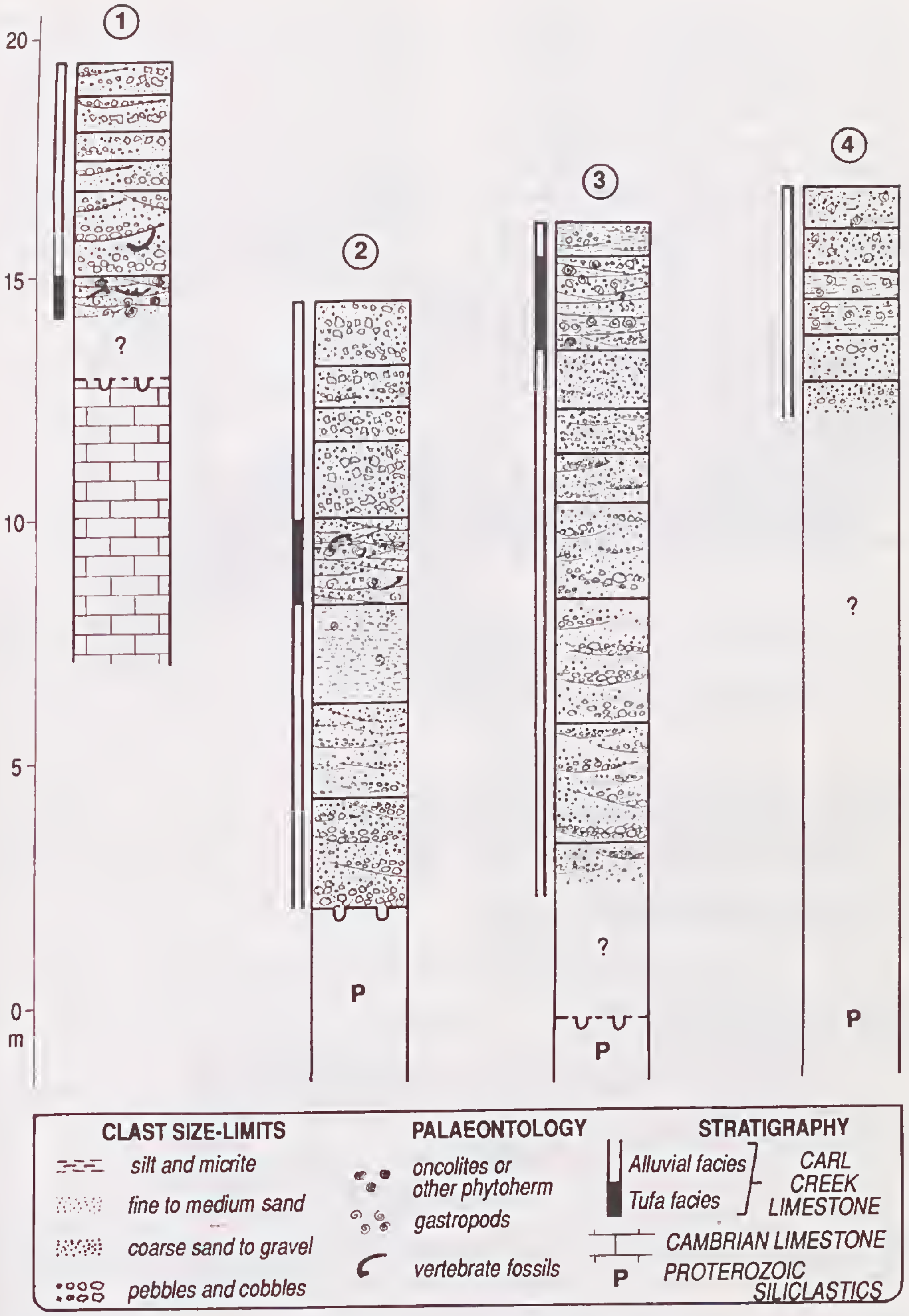


Fig. 5. Selected stratigraphic logs of the Carl Creek Limestone, from locations shown in Figure 3b. Complementary stratigraphic information is given in Figures 6 and 7. No tufa facies have been recognised in the northeastern (downstream) outcrops of Carl Creek Limestone, where exposure is poor. Lithologies present in the northeastern outcrops correspond most closely with those shown in logs 3 and 4.

Lithologies present in the Carl Creek Limestone are classified where possible by depositional textural criteria according to the scheme of Dunham (1962: see e.g. Pettijohn 1975). The deposit is composed largely of white, pale yellow and orange clastic limestone, including interbedded conglomeratic limestone, limestone breccia, calcirudite, calcarenite, calcwacke and calcilutite. The calcilutites (micritic limestone) are thought to be primarily of clastic origin because of their association with coarser sediments. With the exception of the calcilutites, the sediments are poorly-sorted and texturally immature. They comprise a distinctive lithological suite accounting for perhaps 95% of the deposit. The remainder consists of mostly of tufa (*sensu* Pedley, 1990), while fissure-fills and cave sediments are the least significant volumetrically. However, the tufas and fissure-fills are of particular interest because they host the bulk of Riversleigh's vertebrate fauna. The stratigraphic sections depicted in Figures 5, 6 and 7 were specifically chosen to indicate the relationship of the tufa facies to the remainder of

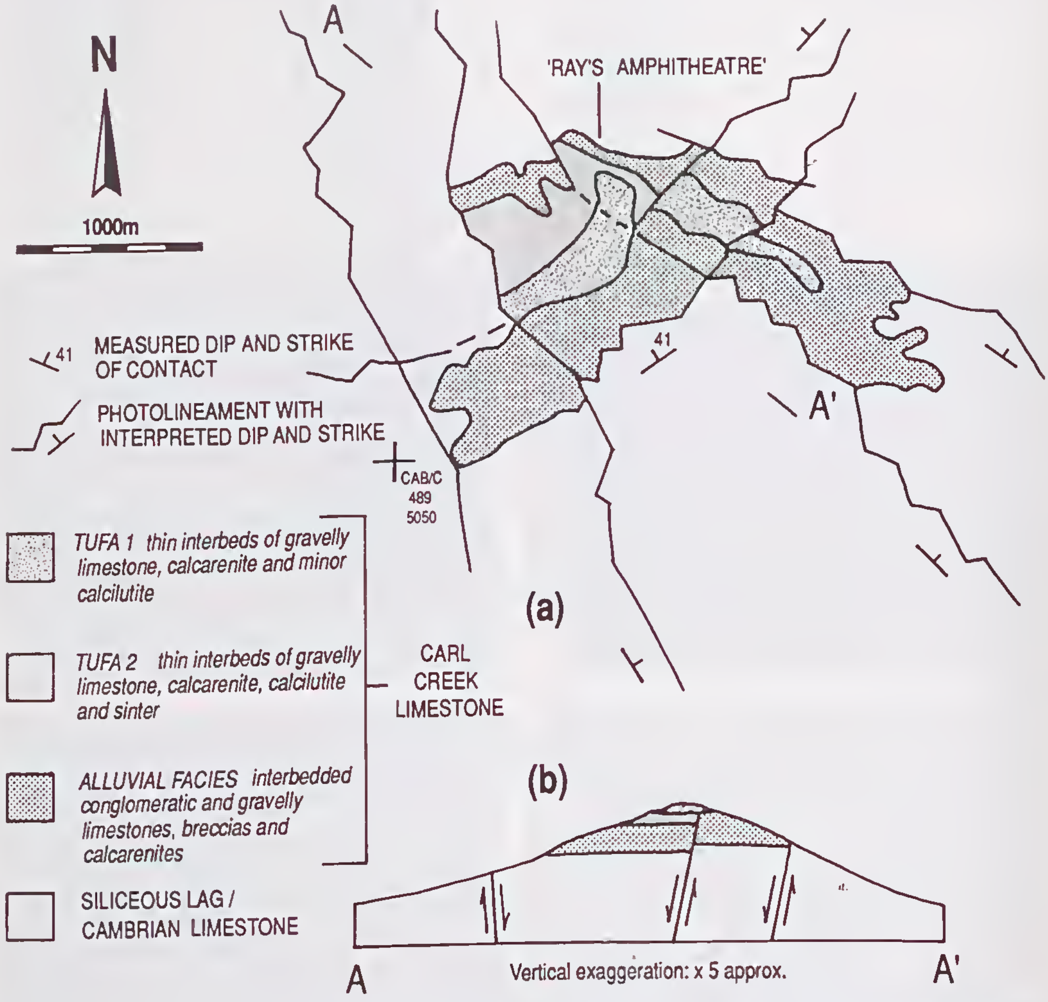


Fig. 6. a, A provisional photogeological interpretation of the eastern part of the "Gag Plateau", with some ground data, showing the relationship of the Carl Creek Limestone to photo-lineaments; **b**, schematic cross-section showing a possible relationship of rock units. These lineaments may represent faults. The area shown is the type locality of the "system C" Local Faunas of Archer *et al.* (1989), who subdivided "Gag Plateau" Local Faunas into three assemblages according to topographic elevation (lowest, middle, highest: Archer *et al.* 1989:65), but on the basis of marsupial stage-of-evolution correlations to South Australian and Northern Territory Local Faunas, recognise "upper" and "lower system C" (Archer *et al.* 1989:55: see Fig. 2, this work). There is a suggestion of a depositional hiatus in "Ray's Amphitheatre" between the two tufa units recognised here. However, the extent of the two units outside "Ray's Amphitheatre" is largely interpreted from photogeology. This figure is intended as a lithostratigraphic hypothesis that may be testable by mammal stage-of-evolution.

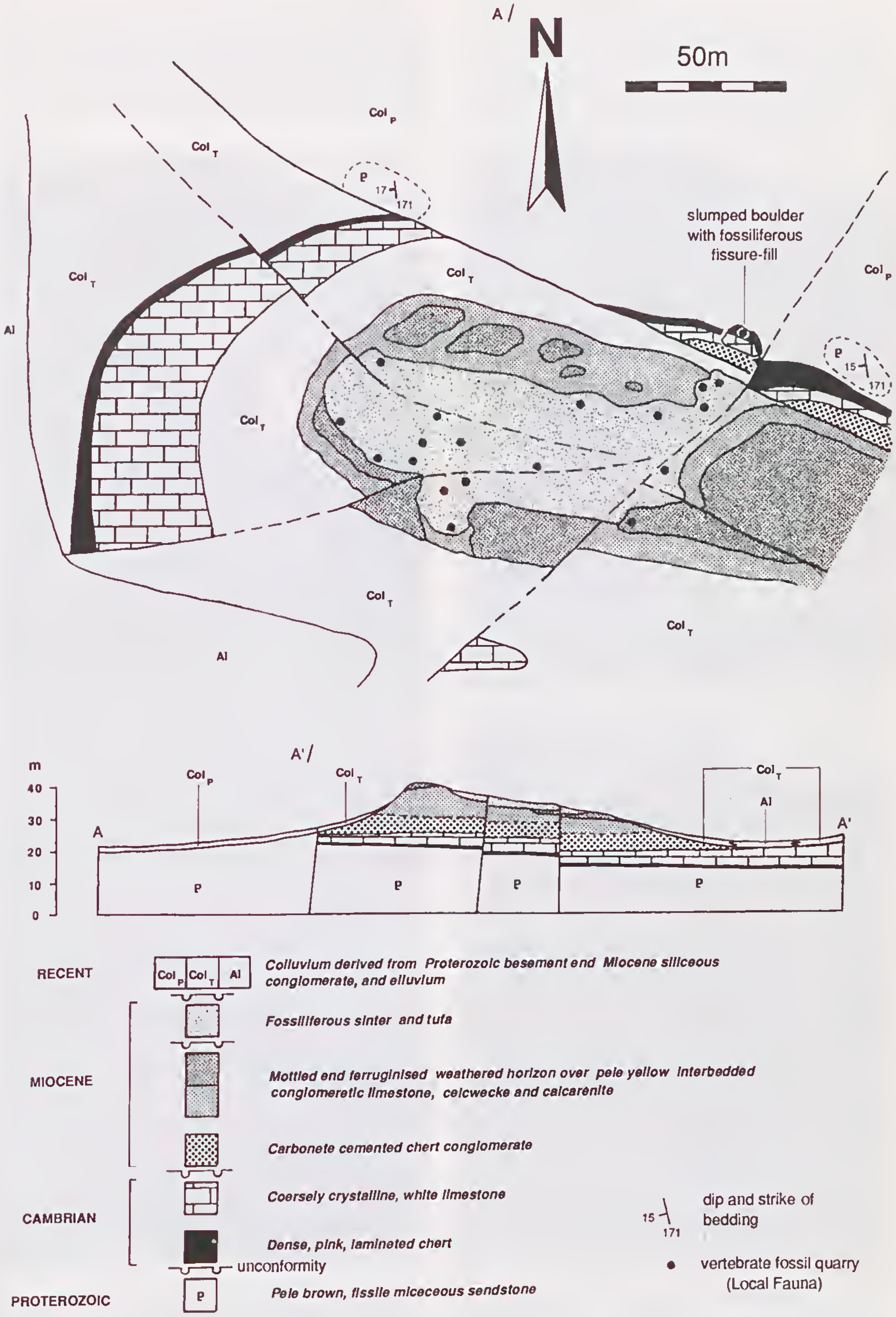


Fig. 7. Plane-table geological map of the "Godthelp's Hill" area, which is the type locality of "system B"-aged Local Faunas of Archer *et al.* (1989). The vertebrate faunas are concentrated in tufas, or in fissure-fills in older limestones. The Miocene mottled-unit is interpreted as an ancient weathered surface.

the deposit, but are not intended to give an indication of the relative volume of tufa present in the Carl Creek Limestone.

The conglomerates and breccias are variously matrix-supported or clast-supported, and are massive to poorly-bedded with normal grading. Clast alignment is random. Where they can be traced in section, these beds are lenticular and do not appear to be scoured into underlying strata. They reach a maximum thickness of one metre,

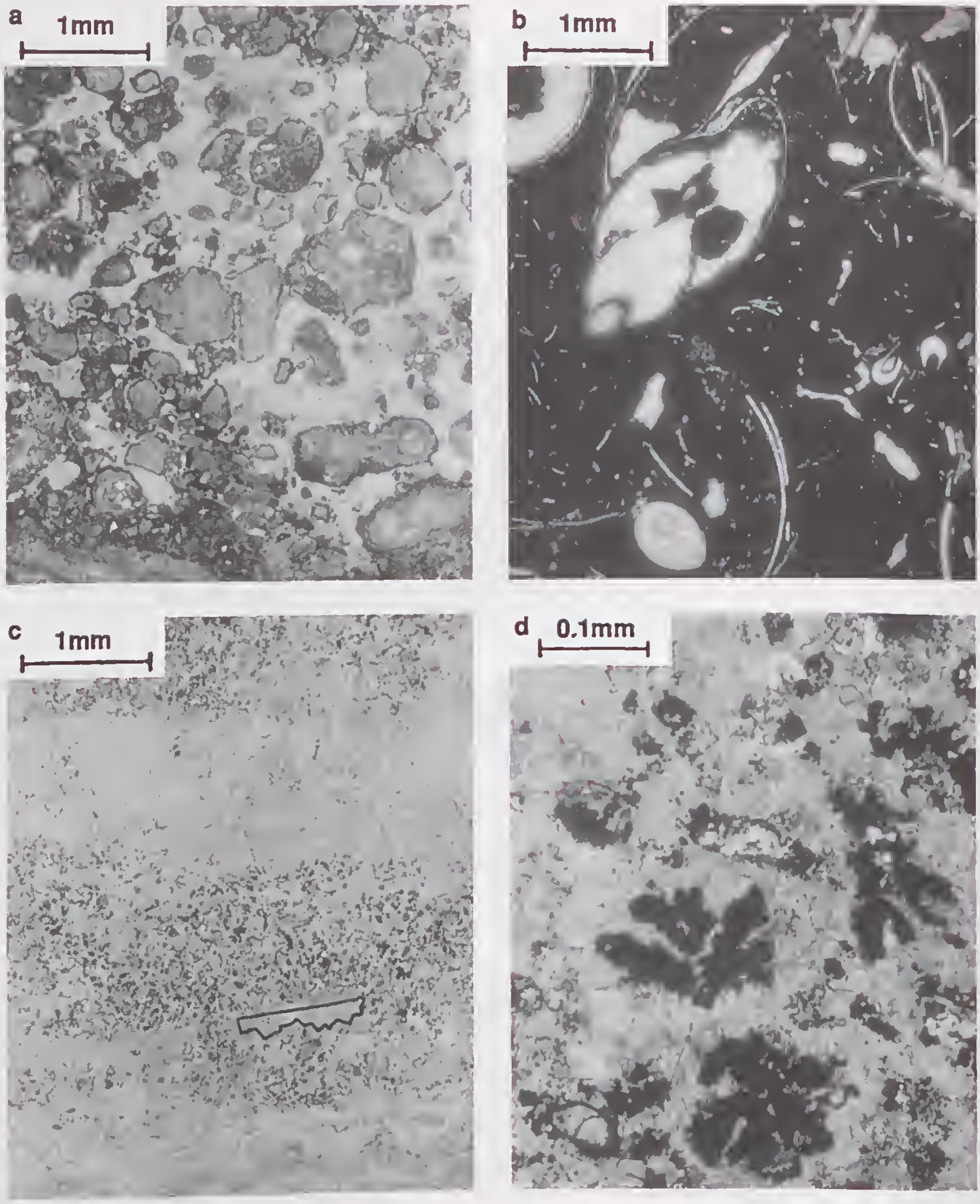


Fig. 8. Thin-sections of: **a**, peloidal calcarenite; **b**, bioclastic calcilutite containing gastropods and ostracodes; **c**, bacterial travertine, Upper Site, "Godthelp's Hill" with **d**, detail of structures resembling the bacterial "shrubs" of Chafetz and Folk (1984). The speckled, bacterial zones in **c**, are interbedded with sinters showing typical algal lamination (bottom). These features suggest that bacteria flourished during periods when physical and chemical conditions were too harsh for algae. The bacterial zones sometimes contain evaporitic calcite plates (one example outlined in ink), morphologically similar to those shown in Figure 12. All plane polarised light.

with horizontal extents of a few tens of metres. Siliceous clasts and fragments of Cambrian limestone are rarely found in these lithologies. Larger limestone clasts are often fossiliferous, containing gastropods, and represent reworked Tertiary limestone.

The clast-supported conglomerates and associated coarser lithologies also show lenticular bed-forms in section, and comprise the bulk of the formation. The coarsest sediments, with cobbles and pebbles sometimes weakly imbricated, occupy the base of scours and grade upwards and laterally into gravelly calcarenites and calcwackes. Such graded sequences are typically one half to one metre thick. Although composed primarily of reworked Tertiary limestone, other rock-types are also present, including chert, sandstone and quartz pebbles and cobbles derived from the basement complex. Siliceous clasts are more common near the base of the Tertiary sequence. Amorphous peloids and reworked Tertiary calcarenite and calcilutite comprise the bulk of the conglomerate matrix and are the dominant fabric-elements of the calcarenites and calcwackes. These grains are typically coated with a thin layer of micrite (e.g. Fig.8a). Gastropod fragments, laminated limestone particles and quartz sand grains are also commonly present. Aquatic gastropods are common, while isolated vertebrate bone-fragments are occasionally encountered. At a few localities the conglomeratic limestone contains a sufficient concentration of bone to warrant quarrying by vertebrate palaeontologists, as described in more detail later.

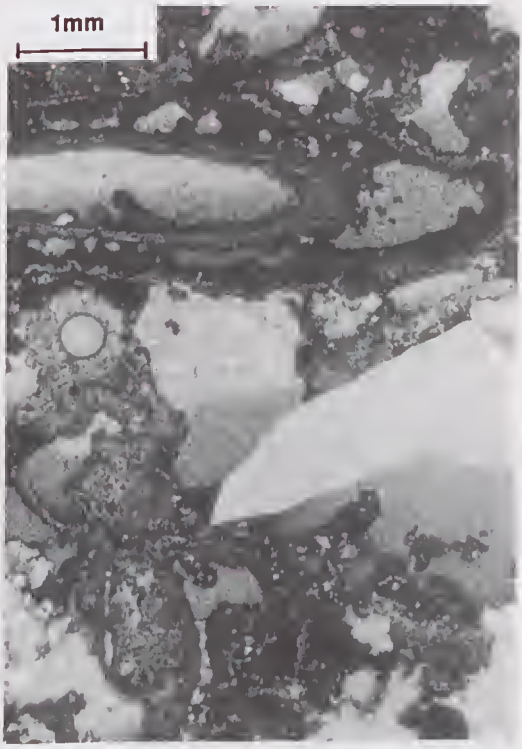


Fig. 9. Thin section of a calcarenite in which the high initial porosity was partially reduced by carbonate silt, and subsequently by calcite cementation, producing geopetal fabrics. Clastic fabric-elements include white, angular chert, probable reworked rhizoconcretions, quartz grains, peloids and larger micritic particles. Plane polarised light.

Some calcarenites are relatively better sorted, with high initial porosities. Primary voids were later wholly or partially filled by carbonate silts during subsequent episodes of sedimentation, producing geopetal fabrics (e.g. Fig. 9). The massive calcilutites contain an abundance of land snails, or freshwater snails and ostracodes (e.g. Fig. 8b), or a mixture of these invertebrates, but no fish or other vertebrate remains were observed. They were deposited in relatively extensive planar beds, traceable on some outcrops for several hundred metres.

Interbedded with, or cross-cutting, the predominantly coarse calciclastics described above is a distinctive lithological suite characterised by the presence of sinters (travertine), stromatolites, various calciclastic sediments and frequently rich concentrations of vertebrate fossils (Figs 6 and 7). The sinters variously line erosional features in the host sediment, or occur as spring-mounds (Fig. 10a) or sheets interbedded with other lithologies. In thin section they typically show algal lamination, though one notable exception from "Godthelp's Hill" corresponds more closely to bacterial travertine described by Chafetz and Folk (1984) from thermal springs in Italy. Dendritic structures described as "shrubs" by Chafetz and Folk (1984) can be seen under the microscope (Fig. 8c,d). Under high magnification, the shrubs appear to be composed of aggregations of spherical structures having dimensions of about five microns which are probably the remains of bacteria. The black material was determined, using a microprobe, to be iron and magnesium oxides.

The stromatolites occur as plane-laminated sheets or as oncolitic-gravel interbeds (Fig.10b). The oncolites show characteristic coarse algal-lamination (Fig. 11a), and the nuclei upon which they have formed include vertebrate bones (Fig. 11b), peloids, laminar stromatolite intraclasts, gastropods, or other calcareous lithoclasts.

Amongst the oncolites are rare, very finely-laminated pisolites, and pisolites showing alternating coarse algal lamination and fine lamination (e.g. Fig. 11c). The fine lamination is indicative of direct chemical precipitation of calcite, without the mediating influence of algae.

Pebble conglomerates, calcwackes, calcarenites and calcilutites, texturally similar to those described above, occur as thin (up to a few decimetre) interbeds between the sinters and stromatolitic lithologies, or are closely associated with them. Oncolites, stromatolitic intraclasts and other phytoherm fragments are common fabric elements in the coarser lithologies. As well as gastropods and ostracodes, they contain aquatic vertebrates including fish, crocodilians, turtles, amphibians and platypus. Terrestrial mammals, birds and reptiles are also present.

Amongst the more unusual lithologies associated with sinters are calcite evaporites and phosphorites. Figure 12a is a grain mount of Recent detritus collected from a dried out pool in Old Napier Downs Cave in the Kimberley of Western Australia. The sparite aggregates are plate-like in three dimensions, with two distinct morphologies present. The first have a planar upper surface, with crystal terminations projecting downwards, and presumably formed by evaporation as they floated on the still surface of a drying pool. Others have crystal terminations on both surfaces, reflecting further crystal growth after the plate had settled to the bottom of the pool. Figure 12b shows a cumulate of morphologically-similar crystals from the "Burnt Offerings Area", and includes a section through a probable bat bone.

A phosphorite containing five species of leaf-nosed bat (Hipposideridae) (Hand *et al.* 1989) is probably a diagenetically altered bat-guano (chiropterite of Hutchinson 1950) formed under a bat roost (Fig. 11d-f). The phosphorite is restricted to the remains of a travertine-lined cavity in older limestone. Associated with it, and not known from any other sites is a red soil similar to those found in modern caves. Thin-sections indicate that the gastropods and algal structures described by Hand *et al.* (1989) from the site belong to a later episode of sedimentation.

Fissure-fills are easily recognised on the escarpments and in outcrop by their generally darker colour and cross-cutting relationships to the host sediment. The larger clasts are typically very angular, and are frequently concentrated in siliclastics relative to the host rock. Some contain enough vertebrate fossils to warrant quarrying (e.g. Fig.7).

Also present are sediments that may be described as matrix-supported breccias on textural criteria. However, they differ from those described above in lacking any evidence of internal stratification or transport, and are typically mottled by iron-staining. The larger clasts are apparently derived from the underlying lithology, and no material is present to suggest any other provenance. Thin sections reveal evidence of incipient soil formation. These deposits have the characteristics of regolith, though no complete soil profile appears to be preserved anywhere in the Carl Creek Limestone. They are commonly associated with the sinters and related rock-types.

Primary voids in all lithologies are filled with sparry low-Mg calcite cements. When stained

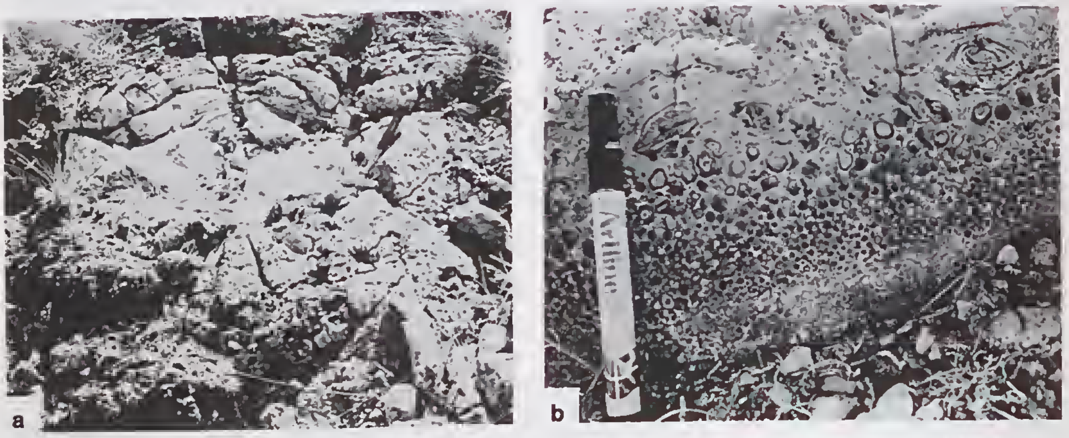


Fig. 10. a, Sinter spring-mound, "Godthelp's Hill". The pick is 35cm long; **b**, Reverse-graded oncolite gravel, Inabeyance Site, "Godthelp's Hill". The marker pen used for scale is 15cm long.

with Alizarin red-S and potassium ferricyanide to distinguish calcite and ferroan-calcite respectively, according to the method of Lindholm and Finkelman (1972), concentric compositional zoning of the cements are apparent (Fig. 13). Such zoning is commonly attributed to rapid and frequent fluctuation in the chemistry of the bulk fluid composition from which the cements were precipitated, or rapid changes in Eh, but other poorly understood factors also influence the

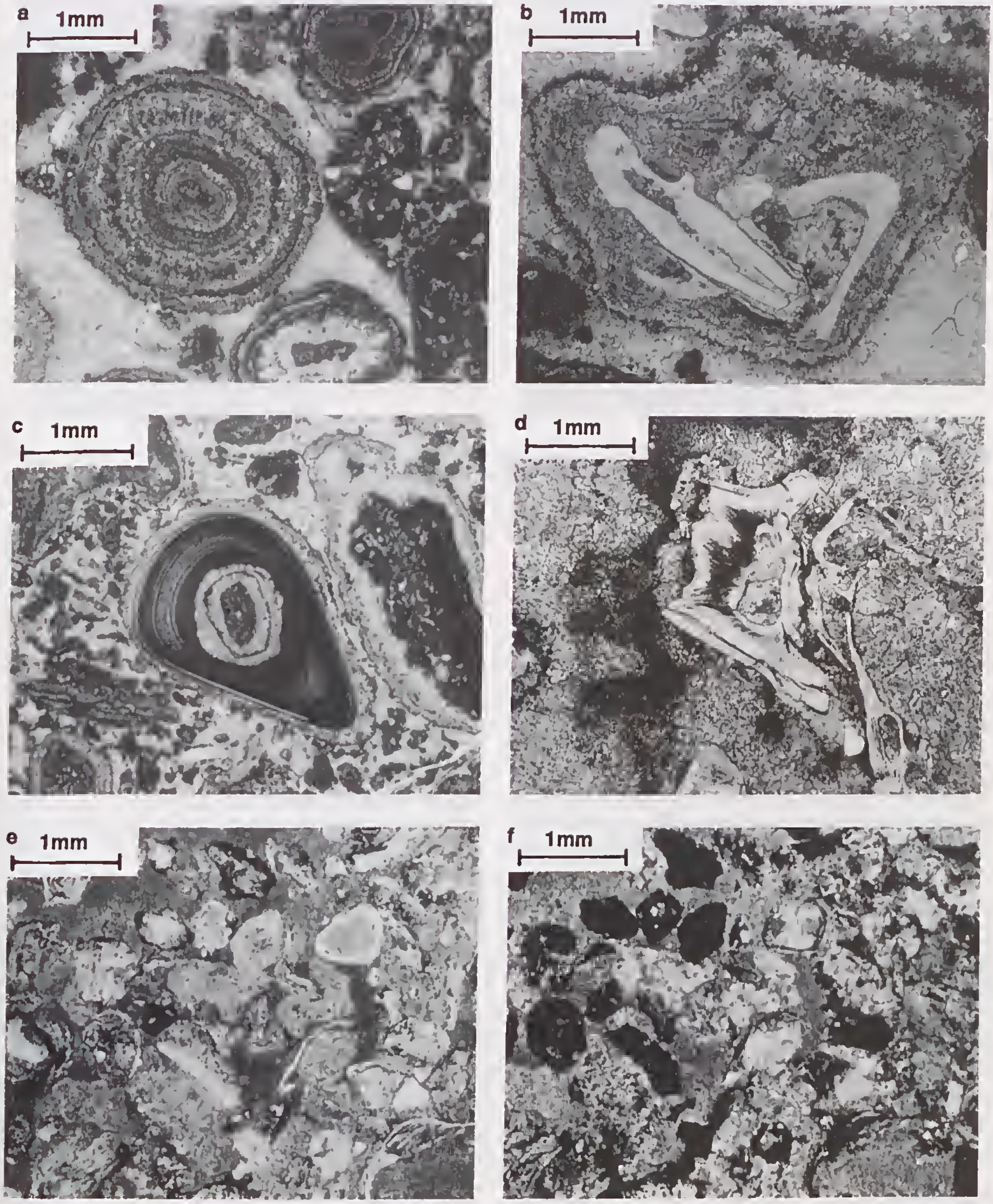


Fig. 11. Thin-sections from Upper Burnt Offerings Site showing: **a**, a typical oncolite; **b**, an oncolite with a bat jaw (shown in transverse section) as the nucleus; and **c**, a pisolite showing alternating zones of coarse algal lamination, and fine lamination resulting from chemical (i.e. abiotic) precipitation of calcite. From Bitesanntenary Site: **d**, a section through a molar and maxilla of a hipposiderid bat, incorporated in **e** and **f**, diagenetically altered bat-guano (chiropterite). The phosphate in the chiropterite occurs as bone, amorphous pellets, and laminated cements (**e**), which appear dark grey or black under crossed polars (**f**).

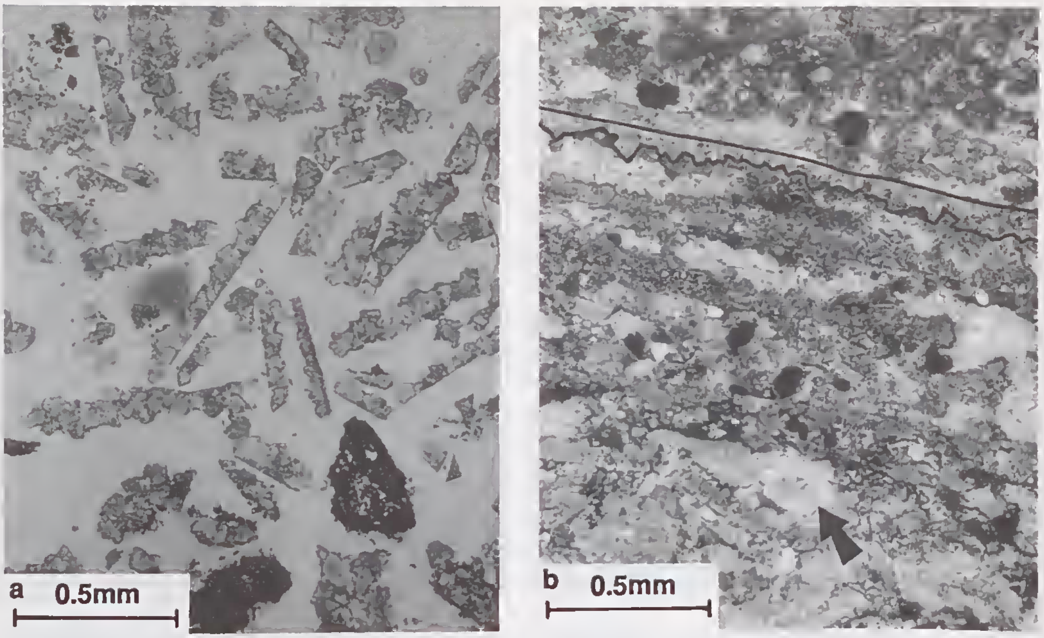


Fig. 12. Thin-sections of: **a**, a grain mount of evaporitic calcite plates retrieved from a dried-out pool in Old Napier Downs Cave, Western Australia, compared with **b**, a cumulate of morphologically-similar plates (with one outlined in ink) from Upper Burnt Offerings Site, Riversleigh. The arrow indicates a transverse section through a probable bat long-bone. Both plane polarised light.

process (Emery and Marshall 1989). A more obvious coarser concentric zoning is also apparent in Figure 13, resulting from alternating bands of spar with a dusty appearance caused by iron-oxide particles included in the crystals, and zones of clear spar. This zonation is attributed to episodes of dissolution in the vadose zone with iron from the ferroan calcite remaining as an oxidised residue, and becoming recemented with the following phase of phreatic cementation. It is taken as evidence of a fluctuating water table. Cement stratigraphy is not consistent between voids, and offers little potential for correlation within the formation. More detailed descriptions of diagenesis, particularly evidence of edaphic processes, in the Carl Creek Limestone are beyond the scope of this paper and are reserved for a future publication.

Structure. Structure in the Carl Creek Limestone is difficult to elucidate because of the lack of marker horizons within the formation. Vague linear features are discernable on air photographs, traversing the Tertiary limestone and in some cases continuing across basement. On the ground in the limestone, these features may appear as very shallow, linear depressions with slightly deeper soils and poorer expression of outcrop. Elsewhere, two to three metre wide, low ridges of silica- and iron-enriched limestone can be traced for short distances across the landscape. On the "Gag Plateau", some of the contacts with basement are planar, but dipping. On air photographs, these contacts appear to zig-zag around (Fig. 6) but in clear concordance with topography.

The best available evidence that at least some of these features are faults that were active in Carl Creek Limestone times comes from a geological map produced by plane-table methods of "Godthelp's Hill" (Fig. 7). "Godthelp's Hill" is bounded to the north by a fault that can be traced to the southeast into the Proterozoic basement, but the other structures shown cannot be followed confidently far beyond the immediate map area. Both Cambrian and Tertiary limestones are, or appear to be, displaced along these structures, with net relative vertical displacement shown in a schematic cross-section (Fig. 7). The Tertiary units show progressively less displacement with decreasing age, suggesting crustal movements during the timespan represented by the Carl Creek Limestone at that locality. However, karstic processes, or some combination of karstic and tectonic processes, might also account for apparent displacements in the Tertiary limestone.

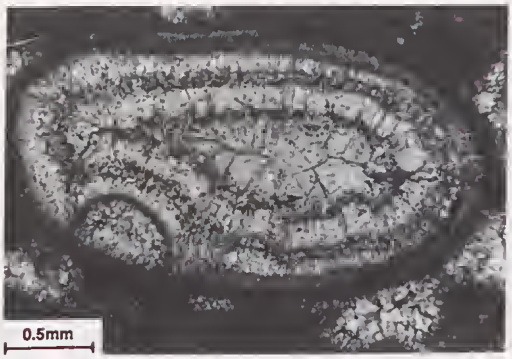


Fig. 13. Thin-section of sparry calcite cement deposited within an ostracode valve, showing coarse, concentric zoning of alternating clear spar and zones containing iron-oxide inclusions. Just discernable in the clear spar in the bottom right-hand quadrant is finer-scale compositional zoning of alternating ferroan and non-ferroan calcite, revealed by staining. Plane polarised light.

Sedimentological interpretation. The sediments comprising the Carl Creek Limestone most closely resemble those described from humid alluvial fans (e.g. Reineck and Singh 1986), cool freshwater tufas (Pedley 1990) and karst terrains (Esteban and Klappa 1983). The term "alluvial fan" implies a fan-like areal geometry for the deposit. Clearly this does not apply to the Carl Creek Limestone which was confined laterally by topographic highs in the basement complex and has a linear areal geometry(Fig. 3). Therefore, Carl Creek Limestone lithologies corresponding to those described from humid alluvial fans are simply assigned to an "alluvial facies" to avoid any misconception about the aerial geometry of the deposit. "Tufa" is used here in the broad sense of Pedley (1990:14) who refers to "all cool water calcareous deposits as tufa regardless of their age and degree of crystallinity". This contrasts with the more widely used definition of tufa as highly porous or spongy freshwater carbonate rich in microphyte and macrophyte growths, leaves and woody tissues. Alluvial fans are generally thought of as being composed of siliclastics, but as the following comparisons suggest, some of Pedley's (1990) tufa facies represent the carbonate analogues of lithofacies described from siliclastic alluvial fans. Pedley (1990:148) makes the analogy but considers the respective scales of the deposits to be a significant difference, with alluvial fans being large-scale compared to tufa deposits.

Climatic factors, topography and source-rock are primary influences on sediments deposited on alluvial fans, which are variously classified as arid or humid alluvial fans, and while ideal end-members might be readily distinguished, there is a continuum between them. Arid fans are well known from desert landscapes, and are formed by ephemeral streams. On the other hand, humid fans are deposited by perennial streams which break their banks during times of flood, sweeping over the fan and reworking older sediments. Alluvial fans of both types are composed primarily of poorly-sorted, texturally-immature, coarse-grained sediments. The sediments are laid down in beds more or less parallel to the surface of the fan, with angles of deposition typically ranging from 3-6° (rising as high as 10°) but as low as 0.19m/km (0.01°) on humid fans. Stratification is moderately developed with boulder and pebble beds alternating with sandy, silty and muddy beds. They are most commonly associated with braided rivers, and form along a front where steeper slopes pass abruptly into more gentle ones. The coarsest sediments tend to be concentrated at the fan head and the finer ones more distally, though small alluvial fans tend to show proximal characteristics over their entire length. Downstream, they grade into fluvial flood-plain facies.

Sediments of the Carl Creek Limestone alluvial facies are interpreted as follows:

1. Massive or normally-graded, matrix-supported breccias and conglomerates that occur in lenticular beds, but are not scoured into underlying sediments, represent debris-flow deposits. The large angular clasts in the breccias were probably not formed by cataclasis. In shape, they resemble colluvial material found on Tertiary outcrop today (Fig. 4d). In the Recent colluvium, the large clasts become more rounded with depth in the profile, suggesting that the angularity results from sub-aerial etching. The same process produces the sharp rillenkarren on limestone outcrop (Fig. 4b,c).

2. Clast-supported cobble and pebble conglomerates occuppying scours in underlying units, grading upwards and laterally into gravelly calcarenites and calcwackes, and having lenticular bed-forms represent braided stream channel-deposits.

3. Massive calcilutites containing an abundance of land snails, or freshwater snails and ostracodes, or some mixture of these invertebrates, but seemingly devoid of fish fossils or other vertebrates (Fig. 8b) were deposited upon flood plains or in ephemeral swamps.

The predominance of coarse clastic material, textural immaturity, poor sorting, stratigraphic relationships and bedding geometries in the alluvial facies of the Carl Creek Limestone correspond closely with those described from alluvial fans. The presence of an aquatic fauna and very low angles of deposition indicates something akin to an humid alluvial fan is represented. Although the Carl Creek Limestone was restricted laterally, the degree of confinement was insufficient to preclude braiding and deposition of flood-plain sediments, and implies deposition in a relatively broad, shallow valley.

Pedley's (1990) synthesis of existing knowledge of tufa formation is readily applicable to the interpretation of ancient examples such as those occurring in the Carl Creek Limestone. He identifies five depositional environments for tufa, characterised by unique combinations of geometries, bedform characteristics, facies groupings and biotal associations. The five include the perched springline, cascade, fluviatile (braided and barrage), lacustrine and paludal settings.

The primary tufa fabric-element is *autochthonous phytoherm*. Phytoherm constitutes the "factory" in the system, whereby plants, principally cyanobatcria (blue-green algae), bryophyta and liveworts, mediate or modify localised carbonate precipitation. Some spontaneous chemical precipitation may also occur. Included in these autochthonous deposits are *phytoherm framestone*, consisting of an *in situ* framework of erect or recumbent hydrophytal and semi-aquatic macrophytes with interstitial cements and clastic fabric elements, and *phytoherm boundstone*, more commonly known as stromatolite. Phytoherm boundstone may be anchored to the substrate or unattached (*oncoids* and *oncolites*). Clastic tufa deposits are derived from reworked phytoherm and earlier cements, and tufa weathering products. Included here are *detrital phytoherm*, *oncoidal*, *micritic* and *peloidal tufas*, and *palaeosols*.

At this point some further discussion of the distinction of the alluvial facies and tufa facies, as applied to the Carl Creek Limestone, is required. Pedley's (1990) classification is genetic, based on the recognition that the clastic deposits are derived from phytohermal tufa. However, micrite, peloids and palaeosols are not formed exclusively from phytoherm. Palaeosols may form on any limestone terrain, and may yield micrite, peloids and larger particles that may retain no diagnostic evidence of their primary origin. Further, biogenic and chemical activity in calcareous soil profiles can result in the formation of laminated particles (pisolites, rhizoliths, laminar caliche) that may resemble stromatolites formed in the aquatic environment (e.g. Read 1976, Klappa 1978, 1979, 1980). Their distinction is not always easy, especially when reworking may have occurred and the particles are removed from their genetic context. Micritic and peloidol deposits are assigned to the tufa facies only where there is a clear stratigraphic and spatial association with unequivocal tufa deposits such as spring sinters and oncolite gravels, and the scale of the deposits is consistent with that shown in the diagrams in Pedley (1990) where beds are typically only a few decimetres thick. In the Carl Creek Limestone, the tufa facies is a volumetrically minor constituent of the formation. Representative examples of tufas from the Carl Creek Limestone include oncolite gravels (braided fluviatile deposit) (Fig. 10b) and a sinter spring-mound (perched springline deposit) (Fig. 10a).

Although some sinter is present in the "Gag Plateau" tufas (Fig. 6), the deposit is dominated by clastic tufas, including calcilutites containing predominantly aquatic vertebrates. The calcilutites were probably deposited in a standing water body, as evidenced by the presence of articulated fish remains, and are thus interpreted as lacustrine tufas. However, no "bull's eye" areal distribution of lacustrine lithofacies (Pedley 1990) is apparent, and the lithological relationships are more consistent with deposition behind a tufa barrage in a fluvial system, though no such barrage was seen in outcrop.

Bacterial travertine is reported from thermal springs (Chafetz and Folk, 1984), but its presence at "Godthelp's Hill" may simply reflect a localised occurrence of physically or chemically harsh conditions favouring the growth of bacteria over algae, such as might occur in a shallow, drying pool subject to high water temperatures and saturated with respect to calcium carbonate. The presence of calcite evaporites (Fig. 12), finely-laminated pisolites formed by chemical precipitation, and pisolites showing alternating zones of oncolitic and abiotic (chemical) lamination (Fig. 11c) may support this interpretation. Risacher and Eugster (1979) report the present formation of similar pisolites (pisoliths) at spring-fed surface pools in playa environments of Bolivia. Calcite evaporites are also known to accumulate in caves (e.g. Fig. 12a), while pisolitic speleothems known as cave-pearls are morphologically very similar to the pisolites described by Risacher and Eugster (1979). As outlined below, caves were present in the Riversleigh palaeoenvironment, and it is possible that the evaporitic calcites represent cave sediments. The finely laminated pisolites might represent cave-pearls that were flushed out of caverns and incorporated into the oncolitic gravels. However, a speleological influence is not favoured for those such as the example shown in Figure 12e because it requires a complicated history of being flushed into and out of a cave. While this is not an impossible scenario, it is considered the less parsimonious interpretation.

Sub-aerial exposure of limestone results in two end-member diagenetic facies: the edaphic or soil facies and the karst facies (Esteban and Klappa 1983). Soil profiles are rarely preserved intact in the geological record because erosion tends to remove unlithified soil products, which become incorporated elsewhere in clastic sedimentary deposits, as already outlined above. Ancient weathered surfaces are preserved in the Carl Creek Limestone (Fig. 7), but are too poorly developed and difficult to trace throughout the formation to serve as a basis for correlation between outcrops.

"Karst" has been used to designate specific landforms as well as geographic regions characterised by these landforms, but results from a complex set of climatic, tectonic, edaphic, hydrologic and petrologic processes. From a geological perspective, "the karst facies represents a net loss of calcium carbonate, although in some stages of karst evolution or in some parts of the profile, it is possible to have equilibrium or gain in the carbonate budget" (Esteban and Klappa 1983). Of particular interest here are the sites in a karst terrain likely to accumulate sediments that are suitable for the preservation of fossils. The two most likely sites are caves and fissures, and both are represented in the Carl Creek Limestone. Ancient fissure-fills are relatively common and some are fossiliferous (eg Fig. 7). Fossils are rarely incorporated and preserved in regolith.

With the possible exception of some speleothems, cave sediments can usually only be recognised as such if there is sufficient supporting evidence to establish the original depositional context, though mineralogy may be useful (Bull 1983). Hydrodynamic processes of sedimentation occurring in caves are no different from those occurring in the open, and consequently there are no diagnostic depositional attributes for water-lain deposits. Phosphorite at "Bitesanntenary Site" (Fig. 11c,d and e) appears to be confined to a travertine-lined cavity, is associated with red soil resembling that commonly found modern caves, and contains a rich bat fauna. It probably accumulated under a bat roost.

A depositional model for the Carl Creek Limestone. The relationship between the karst, tufa and calciclastic alluvial fan facies is shown schematically in Figure 14. In earliest Carl Creek Limestone times, tufa deposits were formed in, and by, small perennial streams sustained by a regional groundwater system. The groundwater was discharged at a springline along an already dissected and karstified escarpment of Cambrian limestone. During periods of base-volume discharge, turbidity was low, favouring phytoherm tufa formation. During periods of higher flow, when the water table was elevated, perhaps in response to seasonal climatic influences, the streams became swollen. The phytoherm was broken down and transported to lower-energy environments, forming clastic tufa deposits.

During infrequent but intense storm events, rates of precipitation on the plateau and escarpment exceeded rates of infiltration to the water table, resulting in overland flow. Soil products and accumulated debris on the interfluves became saturated, some becoming mobilised as debris-flows. On the dissected escarpment, intermittent streams began to flow, charged with high sediment loads. Some joined the perennial streams, contributing to their flooding.

At the break in slope at the foot of the escarpment, the streams broke their banks, sweeping across earlier outwash as braided streams. Current velocities dropped abruptly in response to the low channel-gradients, resulting in the deposition of coarse, poorly-sorted and texturally immature sediments. The coarsest material dropped out first in the channels, followed by finer bed-loads that travelled further downstream or spread laterally to be deposited as over-bank sediments. Suspended sediments travelled the farthest, eventually settling out on flood plains or in extensive ephemeral swamps. The floodwaters subsided rapidly as they percolated downwards through older, porous alluvium. Phytoherm tufa formation recommenced at or near the springline with the return to base-flow conditions.

Over time the escarpment retreated to the southwest through erosion, while the topographic

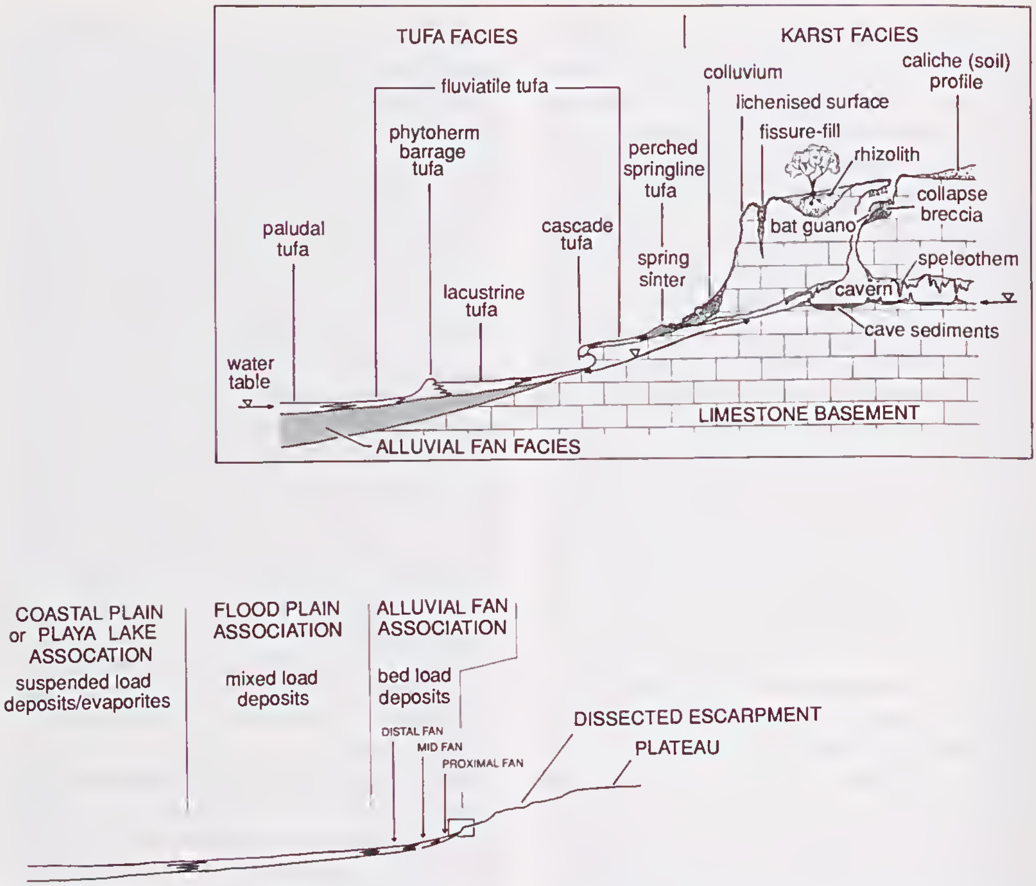


Fig. 14. Schematic cross-section through a fluvial system, showing sedimentary associations and the relationship between the alluvial fan, tufa and karst facies.

position of the spring-line varied according to the position of the water-table. The influence of topography and fluctuating water table on subsequent sedimentation is shown in schematic sections in Figure 15. It is implicit in the model that the relative position of the water table may have varied under the influence of tectonism, long-term climatic variations, or changes in base-level of discharge possibly as a result of eustasy.

Palaeoclimatic evidence from the Carl Creek Limestone. The interpretation of climatic conditions prevailing in the region during Carl Creek Limestone times is developed from two sedimentological principles:

1. In the terrestrial environment limestones erode principally by dissolution, but as outlined above, soils form on limestone terrains and these weathering products may be mechanically transported and deposited as clastic limestones. Tufa is formed principally under biogenic influence, and represents localised re-precipitation of calcium carbonate, which may be reworked as clastic detritus. Whatever their origin, clastic limestone deposits can only accumulate where the rate of dissolution is less than the rate of clastic alluviation.

2. The term "limestone" is applied to those rocks in which the carbonate fraction exceeds the non-carbonate constituents (Bates and Jackson 1980). Thus limestones can only form in environments where non-carbonate sedimentary input is less than the rate of carbonate sedimentation. This applies universally to the marine, lacustrine, fluvial and terrestrial environment.

Alluvial fans are best developed in arid to semi-arid, and subarctic regions: regular heavy rains seem to inhibit their formation (Reineck and Singh 1986). Calciclastic humid alluvial fans are most likely to form in a relatively dry, but not arid climate: wet enough to facilitate calcareous soil formation and perhaps sustain spring-charged perennial streams, but not so wet

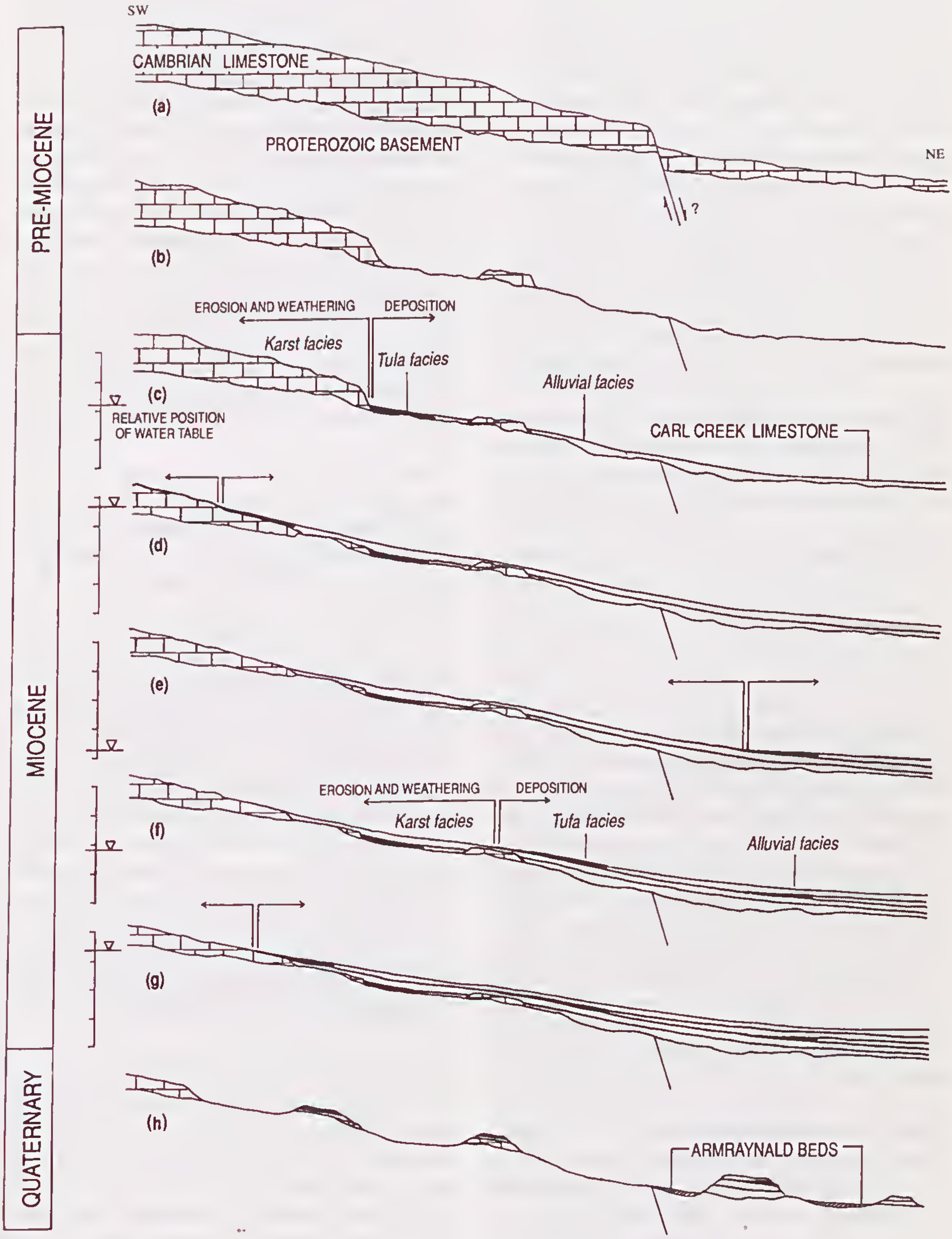


Fig. 15. Schematic cross-sections along the palaeo Gregory River drainage system through time: **a**, formation of an escarpment of Cambrian limestone; **b**, scarp retreat through erosion; **c** to **g**, a depositional model of the Carl Creek Limestone, showing the influence of a fluctuating water table on stratigraphy; **h**, the present landscape after reduction of the Carl Creek Limestone to small mesas. The Armraynald Beds are probably Pliocene.

that the rate of dissolution exceeds clastic carbonate alluviation.

The Gregory River valley was formed in pre Carl Creek Limestone times. In the study area, Cambrian limestones of the Georgina Basin were already stripped off to expose Proterozoic basement by Mesozoic times, as evidenced by the deposition of the late Jurassic or early Cretaceous Mullamen Beds directly onto Proterozoic rocks within the areal limits of the Georgina Basin. The Mesozoic sediments are composed of conglomerate, quartz sandstones, sandy siltstones and siltstones and represent a fluvial facies. Some siliceous clasts incorporated into the Carl Creek Limestone appear to have been derived from Mesozoic sediments, while others resemble Proterozoic rocks. Thus, by Carl Creek Limestone times, siliceous rocks were already exposed in the drainage. Following deposition of the Carl Creek Limestone during the Miocene, and a subsequent period of erosion, the Gregory River valley was again alluviated by the ?Pliocene Armraynald Beds. The Armraynald Beds are a siliceous fluvial deposit consisting of clay, silt, sand and minor conglomerate, with some minor travertine. Today, the Gregory River is cutting down through the Armraynald Beds. Calcareous soils are forming on the limestone outcrops, and colluvium flanks the mesas, but the stream channels contain very little clastic carbonate material. The Gregory River is dammed by barrage tufas, and while the sediments in the impoundments behind the barrages are limy, they do not represent an aggrading clastic limestone deposit and are probably regularly flushed out during the wet season.

The geological history of the ancient Gregory River valley and the interpretation of the origin of the Carl Creek Limestone indicates that a source of carbonate was a necessary condition for the deposition of the Tertiary limestone, but not a sufficient one: a mechanism responsible for the preferential mobilisation and preservation of clastic carbonate over siliceous material must have been in operation. Compositionally-mature, siliceous sedimentary rocks are less susceptible to weathering than carbonates, and under climatic conditions postulated for the formation of the Carl Creek Limestone, siliceous outcrop was likely to yield detrital weathering products at a lower rate than limestone outcrop. This factor, combined with reduced rates of limestone dissolution, resulted in the valley being alluviated by clastic carbonates, in a deposit showing many of the characteristics of humid alluvial fans.

Whitehouse (1940), like Cameron (1901) before him, postulated relatively dry conditions during Carl Creek Limestone times. Cameron (1901) envisaged the Carl Creek Limestone as having formed in an inland sea, into which carbonate-rich streams drained. During times of drought, the carbonate was deposited in response to evaporation. Tedford (1967) also postulated the former presence of a lake, explaining the coarsely-textured sediments from which he collected the Riversleigh Local Fauna as marginal deposits, derived from reworkings of older material deposited during high-lake levels. While lacustrine facies are interbedded in the Carl Creek Limestone, the remaining outcrop does not support the idea that the formation as a whole was deposited in a lake basin: there is no evidence of the vertical succession and concentric zonation of lithofacies characteristic of lacustrine basins.

Whitehouse (1940) observed that fresh surfaces of Carl Creek Limestone usually had "a brecciated appearance", but he nevertheless considered the recent phytoherm tufas forming on the Gregory River a suitable analogue, without explaining the great textural differences. His palaeoclimatic interpretation is quite succinct:

> "...it seems most reasonable to suppose that the *Helicidae* Limestone in question was deposited in a valley between the Cambrian limestones in the west and the late Pre-Cambrian quartzites lying to the east; and that the deposits were formed by precipitation from highly calcareous waters (similar to those at present) issuing from the springs along the Cambrian limestone front, springs that were greater in volume than any within the region to-day. That there could have been deposition of such a thickness of compact limestone over such a great area suggests a period of relative aridity when evaporation was high and there was little influx of surface waters to dilute the supply from the springs."

His conclusion accords well with the palaeoclimatic inference presented here, but what was more important at Riversleigh than the volume of spring discharge, was the balance between the rate of carbonate dissolution, carbonate precipitation as a result of biological activity, and calciclastic deposition. The volume of sediment deposited was dependent on this balance and the period of time over which the balance was maintained. Whitehouse (1940) surveyed other limestone formations of apparently similar age cropping out over western

Queensland and the eastern part of the Northern Territory, citing additional evidence for arid to semi-arid conditions across northern Australia. As explained below, evaporation was probably a more important factor in the accumulation of some of these other limestone formations.

Pedley (1990) identifies environmental conditions apparently favouring tufa formation, based on his studies of Quaternary and Recent examples from Europe and North America and other examples described in the literature. None of these deposits appear to be associated with an extensive deposit resembling an alluvial fan such as that comprising the bulk of the Carl Creek Limestone. Tufas apparently achieve their best development in warm temperate climates that are humid enough to sustain a relatively stable groundwater system. The area of tufa deposition is generally well-forested (Pedley 1990).

CHARACTERISTICS AND ORIGIN OF OTHER MID-TERTIARY LIMESTONE FORMATIONS

The most comprehensive summary of the geology of mid-Tertiary limestones is that of Lloyd (1965a), though Whitehouse (1940) and Paten (1960) are also useful, and more recent discoveries are published in Bultitude (1973), Sweet (1973) and Randal (1969). The rock-types, degree of silicification, topographic expression and association with present drainages are remarkably constant over the region (Lloyd 1965a). The limestones are generally less than 30m thick, and many formations crop out as small mesas, buttes or low ridges in linear belts along present watercourses. Some are interbedded with siliclastic sediments which may be somewhat calcareous. Limestone lithologies include travertine, "travertinous limestone with a brecciated or pellety appearance", nodular limestone, limestone conglomerates, calcarenites and calcilutites or micrites. They are variously described as being crystalline, amorphous or earthy. Generally they are crudely or massively bedded, and the fossiliferous ones commonly contain gastropods, ostracodes and oogonia of charophyte algae, or more rarely, pelecypods, vertebrate remains and the foraminiferan *Ammonia beccarii* (Lloyd 1965a, 1965b; McMichael 1965).

The fossiliferous deposits have been variously interpreted as ancient valley fills, or lacustrine sediments deposited in series of small lakes along old watercourses. Some of the micritic sediments are thought to result from chemical deposition rather than clastic deposition. Other limestones are unfossiliferous, and do not appear to be sedimentary deposits, but represent ancient calcretes, formed by edaphic processes. Their topographic expression is similar to that of the sedimentary limestones and are generally thought to be of similar age. Calcretes are also useful as palaeoclimatic indicators, being characteristic of warm areas with limited precipitation (Goudie 1983). Goudie (1983) indicates that annual precipitation rates of between 400 to 600mm per annum are optimium for calcrete formation, though this may also occur at higher rainfalls in exceptional circumstances. All the limestones are silicified to some degree as a result of post-depositional weathering: the more silicified ones are described as chalcedonic limestones, chalcedony or grey billy.

Little is known of the geochemistry of the northern Australian limestones, but they appear to be mostly low Mg-calcite. Minor dolomite is reported from the Austral Downs and Brunette Limestones (Randal 1966a, 1966b). Compositionally, the Cadelga Limestone of the Lake Eyre Basin ranges from slightly dolomitic limestone to dolomite, and was formed by chemical precipitation under mildly evaporitic conditions (Wopfner 1974). Wopfner (1974) reports gastropods, ?diatoms and algal structures in the formation, while a thin-section prepared from dolomite from the Etadunna Formation, courtesy of Neville Pledge, contains gastropods, ostracodes, the foraminiferan *Buliminoides* sp. cf. *B. chattonensis* (see Lindsay 1987) and small, triangular, thin-walled structures resembling palynomorphs. The South Australian dolomites and dolomitic limestones thus share some similarities with the northern Australian limestones. The northern limestones are here envisaged as forming under similarly arid to semi-arid climatic conditions but representing a somewhat different facies.

The various mid-Tertiary carbonates were deposited in several sedimentary basins, but can be related to each other through a hypothetical model of a single hydraulic flow system, composed of both surface- and ground-waters. Under arid to semi-arid conditions, most rainfall was quickly recycled to the atmosphere by evapotranspiration; most streams were probably intermittent, flowing only after heavy rainfall, and surface runoff from the continent was low. In a generally flat landscape, with duricrusted weathered-surfaces, siliclastic sediment yield was low, and mobilised only after heavy rainfall. A small percentage of the precipitation reached the watertable and recharged the groundwater system. The groundwaters became enriched in dissolved carbonates derived from widespread Proterozoic and Palaeozoic marine dolomites and limestones through which they flowed. Where the groundwater was discharged at perennial springs high in the flow-system, tufas formed and texturally immature calciclastic sediments were deposited as a tufa-calciclastic alluvial fan association (e.g. Carl Creek Limestone). Biogenic tufas are composed of low-Mg calcite, and the preferential removal of calcium resulted in an increase in the Mg:Ca ratio. Such downstream enrichment in magnesium is reported from Recent tufa deposits (Stoffers 1975). Further downstream, the alluvial fan sediments grade into fluvial flood-plain deposits (Fig. 14). The clastic carbonates are finer, better-sorted, and texturally more mature (cf. lithologies yielding the Bullock Creek Local Fauna, Camfield Beds: Murray and Megirian 1992). The finest sediments are micritic, and may have formed either as clastic deposits on the flood-plains or in permanent or ephemeral lakes and swamps, or by chemical precipitation under evaporitic conditions, or by some combination of the two (? e.g. Austral Downs and Brunette Limestones).

Along the groundwater flow-line, evapotranspiration further increased the concentration of salts, while deposition of biogenic low-Mg calcretes resulted in downstream increase in the Mg:Ca ratio. Groundwaters and surface waters were exchanged along the flow-system, depending on the hydraulic gradients between them, but a net result was downstream enrichment of magnesium, and deposition of Mg-enriched limestones as chemical sediments, culminating in precipitation of dolomite in saline-lake or playa environments (e.g. Cadelga Limestone, Wopfner 1974).

PALAEOCLIMATOLOGICAL EVIDENCE FROM OTHER DATA SETS

Distribution of sediments containing palygorskite-group minerals. Depositional environments, age and global distribution of palygorskite deposits are reviewed by Callen (1984). The palygorskite-sepiolite group of minerals are fibrous magnesium clays including palygorskite (attapulgite), sepiolite, pilolite, loughlinite, franclandite and others. They occur in both the marine and continental environments. On continents they form by crystallisation in calcareous soils of arid and semi-arid regions and are one of the few useful palaeoclimatic indicators among the clay minerals. Ancient and Recent examples of non-marine palygorskite are associated with dolomites, limestones (including calcrete), fine or sometimes coarse clastics, and sometimes with evaporites, phosphates and cherts. The associated dolomites are frequently of the type formed in a zone of mixing of Mg-charged freshwaters and waters of saline lakes and playas. They precipitate or form within a sediment in conditions less saline than those conducive to gypsum precipitation and are thus often found around the periphery of evaporites or interbedded with them (Callen 1984). The distribution of the palygorskite facies during the mid-Tertiary is shown in Figure 1c, and encompasses the distribution of limestone and dolomite of similar age.

Inferences derived from models of palaeo atmospheric-circulation. Kemp (1978) reconstructed palaeo atmospheric circulation patterns across Australia for the Cainozoic, based on oxygen-isotope data for ocean surface temperatures derived from deep-sea cores. She postulated relatively dry conditions across the northern half of the Australian continent during the Miocene, but was unable to find geological evidence to support her model. Gypsiferous silts and barytes in the Camfield Beds (Randal and Brown 1967), and the distribution of carbonates and palygorskite support her hypothesis.

Bowler (1982), investigating the origin of Australia's desert regions, also used palaeo ocean-temperature data to postulate that sub-tropical high pressure (STHP) cells first formed in the early Miocene, south of the Australian continent. Most of the world's desert regions today are situated in the sub-tropical high pressure belts. The cells moved northwards through the Miocene in response to Antarctic glaciation and consequent steepening of the meridional temperature gradient between the equator and the pole, thus overtaking the continent in its northward drift. By the end of the Miocene the cells were positioned over the southern part of the continent in much the same configuration as today.

Palygorskite data suggest that semi-arid to arid conditions moved over the continent from north to south between the Eocene and Pliocene as a result of the northward movement of the continent (Callen 1984:figs 10-12), though the latitudinal shifts of the STHP cells envisaged by Bowler (1982) might still be a shorter-term effect superimposed on the effects of a northward continental trajectory. Available geological data does not provide the necessary geochronological resolution to test the hypothesis.

Palaeobotanical evidence. Lange (1982) reviewed the Tertiary palaeobotanical record for Australia. The mid-Tertiary record is poorly represented in central and northern Australia, and heavily biased to the southeastern and eastern parts of the continent. Reconstructing palaeofloras for the whole continent is difficult. Nevertheless, available evidence suggests that conditions suited to the emergence, radiation and substantial specialisation of eucalypts and other mesically-adapted floristic elements occurred during the Oligocene or possibly somewhat earlier. This represents a major transition from the diverse and apparently hydric floras characteristic of the whole continent during the Palaeocene and earlier Eocene, and popularly thought to represent rainforests. The geographic distribution of the Miocene record is equally poor, but the Miocene shows much the same palynological picture as the Oligocene.

Thus, climatic deterioration, possibly starting in the north and moving through central Australia, is envisaged as a major selective pressure for plant evolution in Australia. As the mesically adapted vegetation, and ultimately the xeric vegetation extended their distributions, the rainforests retreated to the southwest, southeastern and eastern parts of the continent (Lange 1982). While this model is broadly consistent with palaeoclimatic interpretations from other data, little is known of the structure of the vegetation over the region.

PALEONTOLOGY OF THE CARL CREEK LIMESTONE AND PALAEOENVIRONMENTAL RECONSTRUCTION

The palaeontology of the Carl Creek Limestone was reviewed most recently by Archer *et al.* (1989). Detailed taxonomic studies are still in progress, but Archer *et al.* (1989) provide an interpretation of the Riversleigh palaeoenvironment based on an assessment of the Upper Site Local Fauna. On the basis of this assessment, they propose a model of vertebrate evolution in Australia since the late Oligocene.

The distribution of vertebrate fossil concentrations in the Carl Creek Limestone accords well with what is known of the preservation potential of the various depositional facies within the formation. Cave deposits and fissure-fills have already been identified as the most likely sites for preservation of fossils in the karst facies, and their fossiliferous occurrence in the Carl Creek Limestone is mentioned above. The occurrence of fossils in the alluvial and tufa facies is reviewed below.

In general, alluvial fans have poor preservation potential (Reineck and Singh 1986), though a calciclastic humid alluvial fan might be expected to have somewhat better potential relative to a siliclastic one because of its composition. The poor fossil record from alluvial fans probably results from the considerable reworking of the sediments. Some concentrations of bone are quarried from what are interpreted as proximal alluvial fan facies, specifically stream-channel conglomerates, in the Carl Creek Limestone. Fragmentary bones are occasionally encountered in more distal facies, but specimens with biostratigraphic utility (i.e. mammal teeth) are rare.

"Site D" of Tedford 1967 (= "D-Site" of later workers), producing the Riversleigh Local Fauna, is one such deposit, and is dominated by large animals, especially crocodiles, dromornithids (large, flightless ratite birds), and various diprotodontid marsupials. Smaller animals are also represented, including chelid turtles, fish, lizards and small mammals. The following observations pertain to D-Site material prepared at the Northern Territory Museum. In some cases, bones extracted with acetic acid from single blocks of limestone belong to a single individual. These bones are typically fragmented, with the fragments displaced relative to each other in the matrix, but are readily re-assembled or placed in articulation after extraction. Thin-sections and macroscopic features indicate that post-depositional, incipient pedogenesis produced the breakages and intraformational translation of the fossils. For example, a large crocodile (NTM P8778) extracted from a single block is represented by the right posterior region of the cranium and posterior region of the right dentary (Willis *et al.* 1990), as well as a complete atlas and axis complex, other anterior cervical vertebrae and cervical ribs, and a set of nuchal osteoderms. The association indicates the animal was still articulated when buried. Other fossiliferous blocks contain numerous large bones of a number of large species: small bones of large animals (e.g. foot elements) are underrepresented, and small species are very poorly represented.

The preservation suggests that concentration of bone in this lithofacies is either an artifact of the rapid burial of articulated remains, or results from the hydrodynamic removal of the smaller bones of disarticulated animals, leaving a lag of the larger skeletal elements. Smaller skeletal elements of large animals, and remains of small species, were presumably dispersed downstream, and their remains were not reconcentrated elsewhere by hydrodynamic sorting.

Pedley (1990) identifies characteristic faunal assemblages of the various tufa facies, and although fish alone are mentioned among the vertebrates, the invertebrates are a guide to the preservation potential of the various tufa lithofacies (Table 1). An example of a detailed study of the palaeontology of a tufa deposit is that Kerney *et al.* (1980), who include a record of the occurrence of moles, voles and shrews in a Recent deposit from southeastern England. Lacustrine and proximal perched springline sediments stand out as yielding the highest faunal diversity. Lacustrine tufas of the "Gag Plateau", and the perched springline associations of "Godthelp's Hill" and the "Burnt Offerings" area host most of the Carl Creek Limestone's Local Faunas.

The Upper Site Local Fauna from "Godthelp's Hill", described in some detail by Archer *et al.* (1989) is an example of a fauna recovered from tufa, and is the basis for their palaeoenvironmental model of Riversleigh in the mid-Tertiary. Lithologies occurring within the quarry include interbedded sinters, oncolite gravels, calcarenites and calcilutites, and constitutes a perched springline tufa. All the lithologies are fossiliferous, though the coarser clastics have the greatest concentrations of vertebrate fossils.

The Upper Site Local Fauna contains gastropods, insects, arthropods, crustaceans, fish, frogs, snakes, lizards, crocodiles, birds, and 63 species of placental and marsupial mammals belonging to 27 different families. Fish, crocodiles and turtles are relatively uncommon, and tend to be small individuals, probably juveniles of the species, suggesting the standing water-bodies were small and represented marginal habitats for these aquatic animals. On the basis of the exceptional mammal species diversity, high proportion of arboreal species, high proportion of folivores, species assemblages interpreted to represent finely-partitioned feeding guilds, and presence of some taxa whose closest living relatives occur in rainforests, Archer *et al.* (1989) interpreted the Riversleigh palaeoenvironment as dense, gallery rainforest probably similar to that persisting today in mid-montane New Guinea. There are no adequate palaeobotanical data available to either test the hypothesis, or to reconstruct the structure of the vegetation over the region. Interestingly, Currie (1991) reports a strikingly poor correlation between tree and vertebrate species richness on the North American conti-

Table 1. Tufa associations, dominant fauna and/or flora, and potential for fossil preservation. After Pedley (1990).

Tufa Association	Dominant Fauna/Flora	Preservation Potential
1. PERCHED SPRINGLINE		
1.1 Proximal	Freshwater gastropods, insect larvae, worms, ostracodes.	GOOD
1.2 Distal	pulmonate gastropods: other taxa rare.	POOR
2. CASCADE	-	POOR
3. FLUVIATILE		
3.1 Braided stream	cyanolith dominated (oncolites)	LIMITED
3.2 Framestone barrage	-	POOR
3.3 Barrage lake	gastropods, charophytes ostracodes, cyanoliths	GOOD
4. LACUSTRINE	algal bioherms, charophytes, diverse gastropods (esp. Lymnaeidae, Planorbidae), bivales (Unionacae), beetles, insect larvae, fish, diatoms.	EXCELLENT
5. PALUDAL	marsh and terrestrial gastropods.	LIMITED

nent, and intimates similar results for Europe and Australia (Currie 1991:45).

Sedimentological evidence for widespread, relatively dry conditions during Carl Creek Limestone time can only be reconciled with the presence of rainforest, regardless of its type (e.g. Webb *et al.* 1984, 1986) if the Riversleigh rainforest was restricted to those parts of the depositional basin of the Carl Creek Limestone where perennial spring-charged streams and a shallow water-table provided suitable conditions. Elevated ground, the extensive limestone plateau to the southwest, and flood plains within the depositional basin, were unlikely to have supported rainforest, though if the annual rainfall distribution was relatively even (in contrast with the highly seasonal monsoonal conditions prevailing today, for example), perhaps a mosaic of woodlands rather than extensive grasslands were present. Any rainforest is envisaged as having been essentially riparian, grading laterally into other vegetation types over relatively short distances. Such an ecotonal situation might well have supported a high faunal diversity.

This suggests an alternative explanation for the high species diversity in the Upper Site Local Fauna. In a landscape with limited surface water, animals occupying a variety of habitats were obliged at times to travel to permanent water sources to drink, or perhaps in the case of frogs, to aggregate to reduce water-loss (see Tyler *et al.* 1990), particularly during a dry season. The fossil record in the tufa facies of the Carl Creek Limestone possibly includes animals from adjacent (though not necessarily very distant) ecosystems ("distant communities"), though at lower frequencies than animals permanently occupying the tufa environs ("proximal community"), in accordance with the model of Shotwell (1955), for example. Archer *et al.* (1989:37) argue that the lack of evidence for transportation is an indication that distal communities are not represented in the Upper Site Local Fauna, and that all the taxa were sympatric within the immediate area. Animal behaviour, rather than hydrodynamic transportation, is another mechanism that might be responsible for the presence of a distant community in a fossil assemblage.

Some of the taxa listed from the Upper Site Local Fauna do not have close relatives occurring in rainforested areas today, or their closest relatives are restricted to mesic and xeric environments (marsupial moles, koalas, ghost bats and potoroos), while some fossil taxa (e.g. diprotodontids, thylacoleonids) occur in other formations whose Local Faunas are compositionally quite unlike the Upper Site Local Fauna, and are not interpreted as rainforest communities, (Lake Eyre Basin Local Faunas: Wells and Callen (1984); Bullock Creek and Alcoota Local Faunas: Murray and Megirian (1992)), though some taxa are possibly derived from restricted stands of rainforest fringing permanent watercourses.

Archer and Hand (1987), and Archer *et al.* (1988, 1989) suggest that Australia's endemic marsupial fauna originated in late Oligocene or early Miocene rainforests such as that postulated by them as occurring at Riversleigh. In their model, some elements of these faunas successfully adapted to progressively more mesic conditions and radiated into other environments through the Miocene, others became extinct, and the remainder were confined to rainforest refugia.

While the drying-out of the continent during the Tertiary, and consequent changes in vegetation may have been the major selective pressure on mammal evolution in Australia, evidence presented or reviewed here indicates that mesic to xeric conditions were already widespread across the continent in earliest Carl Creek Limestone times. Therefore, any Miocene rainforest at Riversleigh probably represented a refugium, and some mammals preserved in the Carl Creek Limestone may have already radiated into the drier habitats.

CONCLUSIONS

1. The Miocene Carl Creek Limestone is diachronous, spanning the complete period of widespread carbonate sedimentation across northern Australia. The formation is composed principally of coarse clastic alluvium showing the characteristics of humid alluvial fans, with minor tufa and palaeokarst facies. The distribution of vertebrate fossils within the formation is consistent with preservation potential reported in the literature, with Local Faunas concentrated in tufas, proximal fan sediments and fissure-fills.

2. Geochemical and physical conditions favouring limestone deposition suggest that the calciclastic alluvial outwash comprising the Carl Creek Limestone could only form under relatively dry, perhaps semi-arid climatic conditions.

3. Miocene limestones from different sedimentary basins across northern Australia can be related to each other through an hypothetical

hydraulic flow system. The Carl Creek Limestone represents the most proximal facies in a fluvial system, and the other formations more distal ones. All formed under similarly dry conditions.

4. Paleobotanical data, palaeo atmospheric-circulation models, palygorskite clay distribution, and the presence of evaporites in the Camfield Beds support the interpretation of regionally dry conditions across northern Australia during the Miocene.

5. Based on an assessment of the mammal component of the Upper Site Local Fauna, Archer *et al.* (1989) postulated the presence of rainforest at Riversleigh during the Miocene. Under the climatic conditions interpreted from sedimentological data, rainforest was probably of very limited extent, confined to the proximity of perennial spring-fed streams and adjoining areas of shallow water-table within the Carl Creek Limestone depositional basin. Thus it is possible that the Upper Site Local Fauna is not a sympatric fauna, but includes elements from distant communities. These distant communities were already adapted to mesic conditions by the early Miocene, and Riversleigh represented a refugium for rainforest taxa.

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